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TV receiver registration to utilize unused frequencies in the TV broadcasting band

Master thesis

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June 1, 2011

Abstract

In this thesis the registration of TV receiver information in a database is introduced to utilize unused frequencies in the TV broadcasting band. The unused frequencies are split in the terms: White space and Gray space. By conducting simulations at three areas in Norway the amount of unused frequencies with focus on the Gray Space is found. The result is evaluated in regards to the level of information retrieved from each TV receiver. There are three knowledge levels evaluated: when the information changes from only knowing the available channels at a location, to having information on which broadcaster delivers TV service information at a household, and finally how the amount of Gray Space changes when knowing the TV usage in time. The available White Space and Gray Space amount is calculated considering a Cognitive radio with transmit power of 100mW and 4 W.

Using realistic TV broadcast environments, the method of introducing an RX receiver database opens for 81-96 MHz of Gray Space in average when considering a Cognitive radio device with 4 W transmit power. This level increases to 109-115 MHz in average when considering a 100mW Cognitive radio device. These levels are present in addition to the White Space of about 200 MHz.

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Acknowledgements

This thesis would have not been possible with guidance and support from several individuals.

First and foremost, my utmost gratitude to my mentor Josef Noll for his guidance and support throughout the course of this thesis and beyond.

Second I want to thank Torleiv Maseng for introduction me to this field and the insight he has shared. And Stig Johannessen from NPT- The Norwegian Post and Telecommunications Authority, which as helped me get a clearer understanding on the TV broadcasting system used in Norway.

In addition I would like to thank the staff and students at UNIK for support throughout my graduate years. I wish you all the best.

Last but not least I thank my family and friends for their moral support and positive remarks, with special thanks to my mother and sister.

This thesis is dedicated to my late father and grandfather.

Hemdan M. Bezabih

1. June 2011

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1 Introduction

1.1 Goal

The purpose of this thesis is to show that if TV- receiver information is retrieved, and their positions are located a better utilization of the TV broadcasting frequencies can be made. This band is unused at certain times and locations, and if the TV reception is not disturbed the unused frequencies can be utilized by another unlicensed service.

The thesis will analyze the potential increase of unused frequencies by using the knowledge on TV receiver locations and the channel usage. There has been work on a database that registers TV- transmitter parameters but by registering TV receivers the amount of unused frequencies will increase.

1.2 Motivation

While new technology is developing the need of more radio spectrum is increasing, unfortunately spectrum is a scarce resource. Research findings indicate that the TV band may be reused by other services if one can guaranty no harmful interference to licensed services, such as TV receivers.

In addition Brown, indicates that registering TV- receiver locations will give a better mapping of unused frequencies in the TV bands [1]. Further, the author lists up different ways of detecting receivers but in the end registering transmitter information is chosen as the best option. In this thesis rather then trying to detect the TV receivers, their location is registered.

Such a database is assumed and presented by Toan et al., they introduce a protocol layer that will contribute to effective sharing of unused frequencies. One of the clients of the protocol presented are passive devices such as TV receivers, their usage are assumed registered through a central database(CDB) [2]. The concept of registering TV receivers is the main part of this thesis.

The static structure of the one -to- many technology, where one has fixed TV stations and mostly fixed TV receivers makes the TV broadcasting band a convenient band to plan further re-use of frequencies.

We know that the location were the TV service is used will vary depending on the area evaluated. At less populated areas there are large areas were the TV service is not used, thus those locations will have a higher amount of unused frequencies. Today, the system does not take advantage of this.

Hopefully writing this paper will be a part of the motion that has started regarding the utilization of unused frequencies in the TV broadcasting band.

1.3 Brief overview

The radio frequency spectrum is a limited resource. The use of this spectrum is regulated internationally and nationally with strict rules regarding frequency allocation. Today this allocation is mainly static; the spectrum is split in bands that are used by different radio services.

The regulation may either be licensed, for instance like the license for FM radio broadcast and television broadcast, were the license holder are given the guaranty of access to the band and the protection against interference from other services. Or it may be licensed exempt meaning the users are not guarantied to get access but has to coordinate with other systems when using the band [3]. These users may for instance be found in the unlicensed band of 2.4 GHz and 5 GHz. The TV band is a licensed band where the TV receivers are guaranteed protection, thus a device wanting to utilize the unused frequencies must be able to give the required protection.

Depending on time and location the usage of the band varies. According to the Federal Communications Commission(FCC), the utilization of assigned spectrum ranges from 15 % - 85 % [4, 5]. The statically allocation method has been seen as an obstacle when it comes to effective usage of the spectrum, because it limits the usage of the band when it's not used by the licensed system.

In recent years much work has been done in increasing the spectrum utilization by accessing this band in a dynamical matter. Dynamical spectrum access is a method that will increase the ineffective spectrum usage by exploiting the limited available spectrum [6].This is done by accessing the band in an opportunistic matter, without interfering with the existing users.

Cognitive radio (CR) is the key technology to access the spectrum dynamically [7]. It can be used to adopt a communication environment, for instance by varying the frequency it operates on. Thus, the technology makes it capable to use and share the band between different services by choosing the best available band. In recent years the most discussed use of the Cognitive radio is using the licensed TV broadcasting band on a secondary basis.

After the switch off to digital TV there has been a re-evaluation on the utilization of the TV broadcasting band. Researches show that allocated band for broadcast services are underutilized [8]. A Cognitive radio in this band may detect unused frequencies and use them at location and times were they are not used by the primary system. This way one can increase the efficiency of the spectrum usage [9].

In 2004, FCC suggested to open up the band for unlicensed secondary usage [10]. Since then there has been much work within this field. Regulators both in USA and UK has committed to unlicensed operations using the unused frequencies in the TV band, which they referred to as White Space. They have also decided that a database must be used to protect licensed services from interference.

Opening the band, thus being able to utilize more spectrum will give us the platform to make way for novel services and applications. The technology talked about for these frequencies are broadband access for rural areas, personal in-home devices and new innovative technology. Technology that are used in the unlicensed band of 2.4 GHz, and 5 GHz can for instance use Cognitive radios to operate using the TV- bands [11].

There are many standards that relate to dynamic spectrum access and also deal with the co-existence of several systems sharing the same band.

- The IEEE 802.22 is the only one dealing with unlicensed operation using the TV White Spaces. IEEE 802.22 WRAN - wireless regional area network is a system dealing with fixed secondary operation using white space frequencies. The system is a fixed to multipoint wireless interface. The base station is fixed and the user equipments is called a customer premises equipment(CPE) located within a cell.

In addition other system has been tried out in the band, White- Fi is a technology having Wi-Fi like properties but using unused frequencies in the TV bands [12]. This has been implemented at the Microsoft campus in Redmond, Washington, USA.

In the longer run the dynamic access may go further then secondary access and also work with different types of spectrum to be able to used the best available spectrum [6].

1.4 Services and application areas

The TV- band has good propagation characteristic [11]. Because of its low frequencies it has low loss per distance that makes it reach longer distances then other frequencies.

In addition it also has better propagation through obstacles which makes it desirable for certain service.

The next sections introduce some services that are thought for the Cognitive radio and also applications explicit for the TV broadcasting band.

1.4.1 Cognitive radio usage scenario

In 2006 Ian F. Akyildiz et al, did a survey on next generation networks [6]. They present the idea and the cognitive radio.They also mention some application areas for the cognitive technology such as leased network, cognitive mesh network, emergency and other wireless network.

- **Leased network**

The primary network can lease its spectrum to other services with the agreement that primary users are not affected.

- **Cognitive mesh network**

Whenever higher capacity is needed a cognitive radio can be used to increase the amount of spectrum. The capacity can then be distributed using a cognitive access point and nodes, thus can add temporary or permanent spectrum to the system.

- **Emergency network**

Emergency networks are established in areas where there have been natural disasters and were a communication infrastructure needs to be installed temporary. The cognitive radio network may then be used to installed the infrastructure by using existing spectrum.

- **Military network**

Another application is in military network were one could use a cognitive network to find secure spectrum band.

1.4.2 Application for the TV band

When talking explicit on applications used in the TV band regulators distinguish between application for high power devices(fixed) and low power devices(portable) [13], [14], [15]. The applications thought for Cognitive devices(CR) operating in the TV band are wireless home networks for future digital homes and smart metering, mobile broadband, and the most worked on - broadband access for rural area [11].

Low power devices The low power devices mentioned may also use unlicensed band but in the future this may not be sufficient, resulting in capacity limitations and interference because of device density. The CR may then be used as an addition to the unlicensed bands [11]. A portable device is evaluated in this thesis to be able to analyze if there are enough unused frequencies for such devices.

Broadband access for rural area: Rural areas usually have fewer technology platforms for internet access. Serving such areas are more expensive than in urban areas because the users live scattered and far from distributors. In urban areas there may be different broadband technology options, were as in rural areas there are few and in some cases not at all [16]. Using the TV- frequencies cheaper technology can be implemented. It is shown that building mobile broadband is 5 times cheaper in the TV- frequency band then in other bands [17]. This makes this an attractive band.

In this thesis a 4 W fixed Cognitive radio device and a 100 mW portable Cognitive device is considered. The 4 W device represents a fixed Cognitive radio that can deliver broadband access to several households, as the IEEE 802.22. Where as the 100 mW represents a portable device, typically used in-home. Current examples of devices using 100mW are WLAN access points [18]. The result found for the portable device may also be used to represent a system that enables Peer to Peer connectivity between Wi-Fi enabled devices.

1.5 Problem statement

This thesis will investigate registration of receiver antenna parameters in a database to protect TV- receivers. The work done so far registers TV transmitters and their service area but does not utilize actual information on TV receiver locations and their channel usage, which leads to an overprotection of the area. The overprotection will vary depending on the locations, channel usage and population density. In some areas there will be large areas that are protected but that don't need protection. By limiting the protection one can increase the unused frequencies.

The database used in this thesis is referred to as the RX database and the database registering the TV transmitter information is referred to as the TX database. The expression "unused frequencies" is a broad term, thus is specified further in this thesis by dividing the term in "White Space " and "Gray Space". The definition is stated in chapter 3 as:

White Space - is considered as frequencies unused by the TV broadcasting system.

Gray Space- is defined as frequencies that are planned to be used by the TV broadcasting system but that are not used at certain locations and for a fraction of time

Based on the TV receiver parameters and calculated protection area for the Cognitive Radios, we will find the percentage of locations containing unused frequencies within an area and the amount of both the White Space and Gray Space found at those locations.

This amount is analyzed by evaluating three knowledge levels. How the unused frequency amount and location percentage change as the knowledge level varies is answered. The knowledge levels are:

1) KN1. Knowing the position of TV receivers and the possible available channels

2) KN2. Knowing the position of TV receivers and the broadcaster one subscribes to

3) KN3. Knowing the position of TV receivers and channel usage on a hourly basis

In addition the result is evaluated for both the fixed and portable cognitive radio devices.

In this thesis the TV broadcasting band in Norway is the focus and therefore three areas are chosen, and the evaluation is executed at those locations.

Further outline of the problem statement will be reviewed in chapter 4.

1.6 Chapter overview

This thesis is built up as follow:

Chapter 2, Background: To get an insight in which TV antenna parameters to register I will investigate the variables affecting the TV reception.

Chapter 3, Related research: Previous work within the field of secondary unlicensed operation in the TV broadcasting band is presented. To get an overview I will present what White Space is and how it can be utilized by secondary unlicensed devices, with primary references to the work done by FCC in USA and Ofcom in UK.

Chapter 4, TV receiver registration: The purpose of the TV registration method is discussed and how the information is retrieved is presented. Also typical values for the parameters presented in chapter 2 are discussed.

Chapter 5, Scenario: The problem statement is elaborate further. The TV broadcasting band in Norway is reviewed and parameters are chosen for further analysis. The last section will review a detailed task on the method used to find the Gray Space.

Chapter 6, CR device parameters: The protection needed for the 4 Watt and the 100 mW Cognitive radio is calculated. The result is used in the implementation.

Chapter 7, Implementation: This chapter present how the tasks of the thesis are solved using matlab and a test case is run.

Chapter 8, Implementation based on real values : The code is implemented for three areas in Norway, and the unused location and the amount of unused frequencies are calculated, for each knowledge level.

Chapter 9, Evaluation of method: Some parameters affecting the result of this thesis is evaluated.

Chapter 10. Conclusion: Summary of thesis and the main finding of this thesis.

2 Background

2.1 Introduction

The information given in this chapter presents the variables that effect the TV reception. The information may be seen in relation to the variables presented in chapter 3 and calculations done in chapter 6.

2.2 Interference affects on receiver antenna when unlicensed operation occurs

To protect the licensed receivers of the TV broadcasting band one must know the interference caused by the unlicensed service. The interference caused may be measured by the S/I ratio received at the TV antenna. This section will review the required S/I ratio and other variables that must be know to protect the TV receiver.

2.2.1 Frequency reuse

The TV broadcasting band is located between 470-790 MHz. Every TV station has a service area which is a contour surrounding a TV station. The contour is defined by a threshold level. This level is the minimum field strength defined by the regulators of the band. The receiver antennas of a TV station channel are located within this contour.

A service area will have a set of channels that are available within its area, these channels and adjacent channels are not used within the area and in nearby service areas. This is an interference avoidance strategy used by the TV broadcasters.

2.2.2 Signal to interference ratio

The signal quality at the receiver antenna is typically described by the signal to interference ratio or carrier to interference ratio [19]. This is the ratio of the wanted signal to the total power of the interfering signals in addition to the noise power. In an interference limited system, like the TV broadcasting band, the noise N is negligible and the signal quality is S/I.

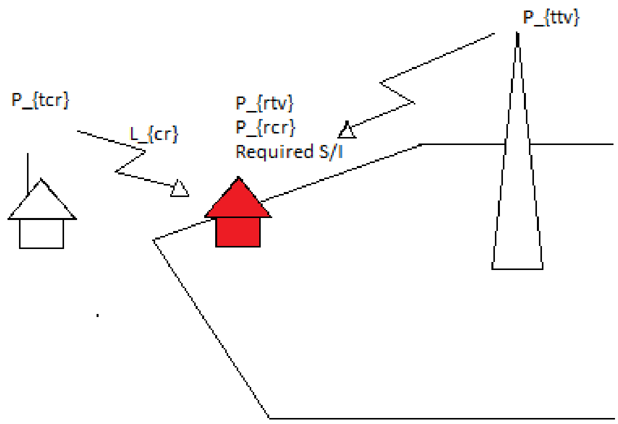


Figure 2.1: Typical scenario of TV antenna and Cognitive radio(CR)

In figure 2.1 a typical scenario of the TV receiver and Cognitive Radio transmitter is illustrated. It is base on information on IEEE 802.22, presented in figure 3. The figure shows a TV transmitter and its service area, the TV receiver is placed within the service area, and the cognitive radio transmitter located on the rooftop of a house. The TV receiver is usually located within the service area, while the cognitive radio can be located anywhere, both within or outside the service area.

The wanted signal for the TV broadcasting system is the TV transmitter signal,P_{rtx}, belonging to the service area the TV antenna is located within.

The interfering signals are unwanted signals received from other TV stations and other sources within the same band, in figure 2.1 the unwanted signal is caused by the cognitive radio operating at a distance close to the TV receiver antenna, P_{rcr}.

To protect a TV- receiver from the secondary system the interfering signal must be limited. Therefore the regulators has put requirements on the minimum S/I needed at the receiver antenna. This requirement sets a limit on the interfering signal, in this case the signal from the Cognitive radio (CR) device.

In section 3.5.1 the C/I limits set by the regulators in UK and USA are presented. For

Table 2.1: Variables affecting the TV reception

	Value
Pt_{cr}	Cognitive radio transmitter power
Gt_{cr}	Cognitive radio antenna gain
Gr_{rx}	Receiver antenna gain
L_{cr}	Pathloss predicted between the cognitive radio and the TV receiver.
L_{other}	other propagation losses which are related to the antennas.

instance for a CR device using the co-channel the required value is 33dB, thus the CR transmit power must be 33 dB below the TV signal.

The maximum signal strenght received by the cognitive radio:

$$I = Pr_{cr} = Pt_{cr} + Gt_{cr} + Gr_{rx} - L_{cr} - L_{other} \tag{2.1}$$

The interfering signal at the TV antenna receiver depends on P_{tcr} signal power transmitted by the cognitive radio, L_{cr} the propagation loss the signal endures on the way and different characteristics related to transmitter and receiver antennas.

Thus, to protect the TV antenna, located at a given position, from the interfering signal we must know:

- required S/I

- P_{rtv}, value of the wanted signal

- P_{rcr}, maximum allowed value of the interfering signal, using the S/I

- Pathloss between CR and TV

The TV receiver parameters are reviewed in chapter 3, how the wanted signal is retrieved is also reviewed in that chapter. In chapter 6 the calculations for the CR devices and chosen pathloss are explained and calculated. First, related work in the field of unlicensed operation in the TV band is presented. Her the required S/I for unlicensed operation in US and UK and the method used to protect the TV receiver are introduced.

For a more detailed and comprehensive information about the calculations and methods used specific for the television broadcast band one can use the final act of 2006 [20], in this chapter a basic formula for the interference and influence of the S/I ratio is introduced.

3 Related work regarding unlicensed operation of TV White Space

3.1 Introduction

In the following chapters the method and rules of secondary access to the TV broadcasting band using White Space is identified. Secondly, the regulatory framework are presented were the emphasis is on the geo- location database; In this thesis defined as the TX database. Thirdly, review of standardization work is done.

First the concept of White Space is described further and the definition of Gray Space is made.

3.2 White Space

Broadcasting services operate in UHF/ VHF portion of the band. Generally the band is prohibited to be used for purposes other than broadcasting, except for services like microphones, remote control, and medical telemetry [11].

After the digital switchover there have emerged vacant frequencies in the band. This is because the digital technology enables a more effective usage of the TV bands: TV channels are distributed using less bandwidth. For instance in Norway, were as before a TV channel occupied a bandwidth of 8 MHz, now several channels can be transmitted using the same bandwidth. In addition to this there are frequencies at given locations that are planned for TV broadcasting but not used at those locations. These locally unused frequencies are referred to as White Spaces [21, 22].

In addition to whole spectrum being unused there are fraction of the spectrum that are unused at given time.

These whole vacant frequencies are not used because of interference avoidance strategies; there is a requirement on the separation distance between TV stations and if they are put to close to each other they would cause interference to co-channel and adjacent channel TV stations. However, if a low power station were to use these locally unused channels, the required separation distance would decrease because it imposes less interference to the licensed users.

Thus, even if two TV stations 3.1 using the same channels are required to have a given distance between each other(red line), a third transmitter with a lower power can use the same channels closer to the TV station without causing interference. It will give the opportunity of using channels that otherwise had not been used by the licensed service, thus giving better spectrum utilization.

3.2.1 White Space and Gray Space

In this thesis the unused frequencies found through the TX database and the RX database are separated. The unused frequencies are either a result of:

- the interference avoidance strategies explained above, resulting in whole frequency band being unused
- or it may be because the TV signal is not received at that given location or for that given fraction of time

To make a clear distinction on the unused frequencies found using the TX database and the RX database, the definition on the unused frequencies are evaluated in this section.

The author considers the original White Space definition as to broad and will therefore specify it for this thesis. *White space is considered as frequencies unused by the TV broadcasting system.*

From chapter 5.2 we know that the TV broadcasting system is found in 470- 790 MHz band and in Norway it occupies a maximum of 40 MHz at any given area were the TV service is given. Thus there is a maximum of 320-40= 280 MHz of unused frequencies that is referred to as White Space.

In addition to this there are locations were the 40 MHz planned for TV broadcasting system is unused.

The Gray space is defined as frequencies that are planned to be used by the TV broadcasting system but that are not used at certain locations and for a fraction of time.

For instance, within the service area thought 40 MHz is used for TV transmission it is not received at every location and for any given time within the service area. There are household that are not receiving the TV signal because they do not have a TV or because they are not subscribing to a given broadcaster. In addition Television is not watched 24 hours a day. At these locations the unused frequencies are referred to as Gray Space. Thus, for these locations the maximum Gray Space amount within the service area is 40 MHz.

The TX database considers the White Space, while the RX database considers both the White Space and Gray Space at an area.

An important note to be aware of is that though there may exist White Space and Gray Spaces, they can not be used before the interference caused by a Cognitive radio is evaluated at those locations.

When using the TX database or the RX database a Cognitive radio is evaluated to be able to calculate the usable amount of unused frequencies. In the next section the unused frequencies accessed by using both the RX database and TX database are presented.

White space found using the TX database:

In section 3.5.2 criterion's on how to use the White Space by the Federal Communications Commission (FCC) and the Office of Communication(Ofcom) are reviewed, they have decided that for a co-channel to be reused it must be found outside the TV service area of a TV station. If the co-channel is unused within the service area it can not be utilized. Likewise for an adjacent channel except when the Cognitive radio device power is decreased. This is done using the TX database that registers the TV transmitter information, explained further in the next section.

Thus the unused frequencies found using the TX database are those outside the service area, and using the definition of this thesis they are called White Space.

The White Space allowed used by FCC and Ofcom and retrieved using the TX database is illustrated using the two upper TV transmitters in figure 3.1. As mention the TX database registers TV transmitter and there TV service area. In the figure the TV stations are transmitting using frequency f1. The brown circular area represents the TV service, and the black circular surrounding the TV service area represent a protection area defined by the regulators. The size of the protection area is defined by the Cognitive radio device transmit power; for a given Cognitive radio there are required distances. This concept is presented later [figure 3.3]. Using the rules; f1 can not be used within the area. The area were frequency *f1* can be reused is represented as the white area. At those locations frequency *f1* is referred to as White Space.

White Space and Gray space found using the RX database:

Despite the definition and rules put for the co-channel and adjacent channel usage, I will in this thesis focus on unused frequencies that is defined by interference limited CR devices rather than the power limited.

In the RX database the TV receiver position are registered and a protection area surrounding that location is drawn, the cognitive radio must then be located outside the protection area to avoid causing disturbance. By registering TV receivers in the database also the unused frequencies within the TV service area can be utilized.

This is also illustrated in the lower left side of figure 3.1. A TV station is shown and quadratic TV receiver is placed within the service area. The protection is as mentioned defined by the interference allowed before the TV reception is disturbed.The locations outside the protection area but within the service area are unused locations were frequency f1 is regarded as Gray Space. For the location were f1 is unused beyond the service are, it is regarded as White Space. By registering TV receivers, the locations within the service area were the channel is not received can be analyzed.

As seen the TX database protects the whole service area which means that the frequencies used at that area cannot be exploited by other systems. If one takes to account the location of the ones using the service and terrain information one could decrease the protected area. Thus, increase the amount of unused frequencies.

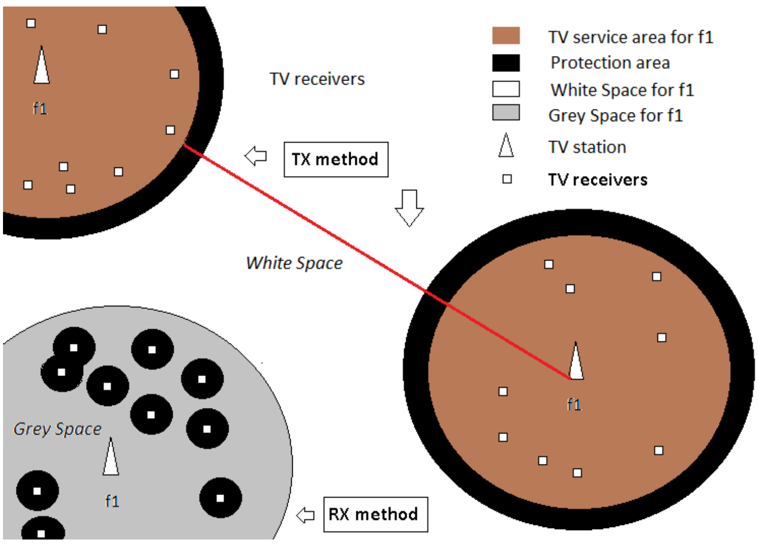


Figure 3.1: The concept of White and Gray Space which can be found using the TX database and RX database, respectively

3.2.2 White Space amount

There has been a lot of work in finding the amount of unused frequencies but the research focuses on the amount of White space rather than the Gray Space. The White Space found depends on location, as described, but also on the transmit power of the CR device, and restriction put on what channels to use [23, 24, 8]. The author Nekovee, has done analyzes on how much available spectrum there is in UK. An average of 150 MHz available spectrum is found in UK, the calculation considers low- power devices with a power of 100 mW and were there are no constrains on adjacent channel usage.

Further they evaluate the amount of available spectrum when there is a restriction on adjacent channels, and the amount decreases to an average of 30 MHz. This is a decrease of 1/5 when considering the adjacent channel restrictions.

If high power transmitters like the IEEE 802.22 were considered the available spectrum would decrease more.

The decrease of 1/5 of the White Space amount depending on channel restrictions indicate that there is an interest in finding a new method that can increase this amount. Adjacent operation of fixed device is a field supported by industry effort like Motorola and Google [13].

In this thesis, by considering the TV receiver sites the restrictions are limited to those areas that absolutely need the protection. Thus, increasing areas where the frequencies are available.

3.3 Method of accessing the White Space

When operating on a secondary basis in licensed bands the main considerations are the licensed users, as also mention in chapter 2. In the TV band this is mainly the TV receivers and wireless microphones.

The prime considerations that must be taken in utilising these frequencies are guarantying no harmful interference of licensed services by the secondary use of the TV broadcasting band [13]. Both in USA and UK there has been considered different methods in accessing and utilizing White Space. There has been research showing that by using a frequency sensing equipment in combination with a geo- database that gives a list of occupied frequencies one can utilise White Space without interfering primary users. This approach is agreed upon by regulators both in USA and UK. [13, 14] The database is the approach that will be investigated in this thesis.

3.3.1 Sensing

By using spectrum sensing technique the spectrum of choice is scanned for the presence of protected services. If the signal is detected the device is not allowed to use the band and must avoid it to prevent interference. The scanning is done on a periodic base to predict changes in the band.

The detection is done by setting a threshold of some level. The level is chosen such that it is capable of registering signals used by licensed users - microphones, TV- transmitter signals etc. Analysis has shown that using sensing alone to detect signals may not be proper to guaranty that licensed users are protected. The main reason is the so called hidden problem, figure 3.2.

Hidden node problem

The hidden node problem may occur if a building or terrain is blocking the sensing of a TV- signal, which may lead to the signal being too low for detection. Causing the Cognitive radio to use a occupied channel which will cause interference to incumbent users [11].

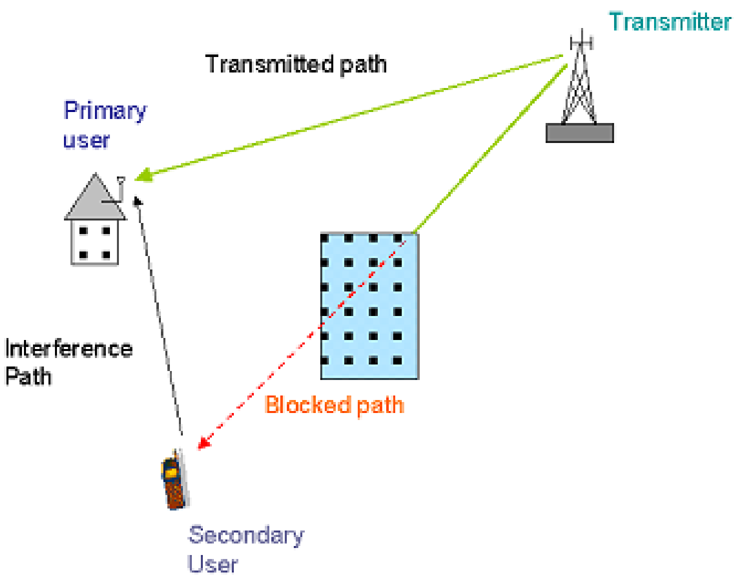


Figure 3.2: Hidden node problem [11]

Registering TV receiver makes it possible to manage those areas that has low TV signal reception, and giving them better protections if needed.

3.3.2 Geo- locationd database: TX database

The TX database will registering TV transmitter and their service area, and in addition other protected devices like cable head ends and locations were microphones are used is registered. Using these information TV receivers within the service area is given protection; the channels available within the service area are set as occupied and are not available for the CR devices. The TX database will then have a list channels that the CR device can use.

An unlicensed cognitive device must be able to supply its geographical coordinates to the database to retrieve those channels that are unused at the devices current location. By doing this the licensed users of the band will be protected. Later in this chapter a review of the technical parameters and further information of the content of the database is presented.

In the RX database of this thesis the focus is on fixed TV receivers, thus microphones and other users of the band are not focus on further.

3.3.3 Discussion

The TX database is based on calculations done on coverage area. A user may receive a signal strength that is lower than the coverage calculation foresees. Thus, they may not get sufficient protection.

In addition there may be users receiving signals at location where they are not supposed to according to the coverage planning. This may lead to situations where it is calculated that the cognitive radio can operate, where in practice they would interfere with TV receivers. This is recognized by FCC, they concluded that protection is only considered for the locations within the protected TV service area. Thus, deviations of that definition are not given protection. No other comments are made by FCC about this subject. Ofcom has not made any decision on this either.

But in practice this must be considered. A CR device operating to close to a TV receiver that is not taken to account by the coverage planning calculations will be disturbed. When using the TX database there is no way of knowing if there is a TV receiver at that location because it was neglected because of misfit between the calculation and practice. In addition if the hidden node problem occurs, the sensing equipment will not be capable of detecting the TV receiver.

TV receiver registration gives the opportunity of managing those areas that has low TV signal reception or that are not calculated for, by varying the protection needed. It is easier to do minor adjustments to the TV receiver at the edge of the TV receiver, thus give protection to users that predictive models are not capable of handling.

3.4 Regulatory framework

In this section a brief review of the frameworks set by the major regulatory agencies is presented. A summary of the parameters presented in the next sections defined by Ofcom and FCC are shown in table 3.1 [14, 13].

3.4.1 US

In 2008 FCC proposed a “Second report and Order in the matter of unlicensed operation in the TV broadcasting bansd“ which established rules regarding operation of unlicensed devices using TV white space [13]. In this report the rules that requires the unlicensed device to use both sensing and database to access the band are presented. An unlicensed device must be able to locate its geographical position to within 50 meters and then access the database to get information about unused frequencies. In principle devices using sensing alone are allowed but needs to be tested by FCC.

The cognitive device is referred to as TVBD -TV band device and they separate between two types of devices; fixed and portable. Fixed devices have a maximum power limit at up to 4W EIRP. Portable devices transmit at up to 100mW EIRP. When they are using an adjacent channel the allowed transmit power is limited to 40mW.

In this thesis the 4 W and and 100 mW Cognitive device are evaluated further.

3.4.2 UK/Europe/ Norway

In 2006 Ofcom released in its ”Digital Divided Review“ Statement to allow licensed exempt use of the TV White space, referred to as the interleaved spectrum, using cognitive radio devices [25]. In 2009 they published a consultation were they put forward technical parameters, much of it similar to those suggested by FCC [14].

In addition Ofcom are discussing sensing alone options. The transmit power of device when the geo- location database is used is specified indirectly by letting the database determine its limit. But further details are yet to be released.

CEPT/EEC

CEPT is working on a draft regarding the utilization of unlicensed devices in the TV band [15]. The group SE 43 is given the task of defining technical and operational requirements of operation in the TV white space. The draft is not studied any deeper. In this thesis the requirment put by Ofcom will be the focus.

Norway

When Norway signed The Final Acts of RRC-06 regarding the frequency plan for digital broadcasting, they signed in addition to the agreement that the TV band frequencies may also be used for other services than DVB-T as long as these services did not inflict interference to adjacent channels [22].

The progress in Norway regarding cognitive radio is on the application side, sensor network for cognitive radios and mobile broadband [26]. Little job is done regarding the database and protection of incumbents. Rather such a database is assumed to exist and to supply unused frequencies for the applications worked on.

3.5 Database technical parameters

This section will investigate the rules and parameter inputs defined by FCC and Ofcom for the database.

The database is as mentioned agreed upon by the regulators but the final technical parameters are not fully defined. Both FCC and Ofcom have done research related to the database and its protection. The parameter can be found in 3.1 . There are mainly two requirements that are review by both regulators.

- Protecting services within the TV station service area

- Operation rules depending on the Cognitive Radio device

3.5.1 Protecting services within the TV service area

In this section a comparison on the parameters defined for the database in UK and US will be reviewed.

Both regulators have decided that all licensed services within the service area must be protected. The method was explained in section 3.3.3. They also have defined maximum co-channel and adjacent channel interference levels. In addition FCC has put requirement on a separation distances between the Cognitive device and the edge of the service area, that are in alignment with the co-channel and adjacent channel interference requirements.

To fulfill the goal of protecting all licensed users within the service area. There are especially two aspects that are evaluated by both regulators.

- Predicting receiver locations
- Maximum co-channel and adjacent channel interference levels that the device can handle

Predicting receiver locations

Both receiver and transmitter information can be used to find the location of TV receiver sites. Both regulators have focused on registering TV transmitter information, by doing so they can use already defined propagation models for DTT to calculate possible receiver locations. All TV receivers within the service area of a TV station are given protection. The service area or contour is defined by a minimum signal level.

The FCC uses a signal level of $41dBu$ as the minimum signal E-field strength needed at the TV receiver for it to be within the service area of a given TV station, this value is valid in the UHF band(ch. 14- 51). Ofcom on the other hand uses a signal level of $50dB\mu V/m$. The units dBu and $dB\mu V/m$ are the same but with different abbrivation in USA and UK.

In this thesis the second method of registering receiver- locations is chosen because it gives a better mapping of the frequency usage.

Interference level

The maximum level of interference a device can handle is defined using carrier to interference level, C/I.

Ofcom has set the C/I level for co-channel interference as $33dB$ and $-17dB$ for adjacent interference. But they state this to be a conservative approach. In their calculations they have taken to account other interference levels and other co-channel and adjacent channel interference sources that may operate simultaneously [14].

Table 3.1: Technical parametres defined by Ofcom and FFC. [14, 13]

Parameters	**Ofcom/UK**	**FCC/ USA**
Bandwidth	$8MHz$	$6MHz$
Min. fieldstrenght for service	$50dB\mu V/m$	$41dBu$
Receiver height	$10meter$	$10meter$
Locations accuracy	$100meter$	$50meter$
Co-channel interference Power limit	$33dB$ As spesified by the database	$23dB$ fixed:$4Watt$
Adjacent channel interference Power limit	$-17dB$ $50mW$	$-26/-28dB$ Portable: $40mW/100mW$

FCC on the other hand operate with a C/I level of $23dB$ for co-channel interference and $-26/-28dB$ for upper and lower adjacent channel interference respectively.

This is defined as that The CR device signal strength must at least be less then $33dB/23dB$ lower then the TV signal strength when the co-channel is used at the CR locations. And for adjacent channel interference the CR signal strength must not exceed $-17dB/(-26dB/-28dB)$ beyond the TV signal. [13]

For instance for adjacent usage if using the $50dB\mu V/m$ minimum signal strength at the edge of the TV service: The Cognitive radio signal strength must be less then $67dB\mu V/m$ at the TV receiver location.

3.5.2 Operation rules depending on CR device type

Depending on the channel type, there are different rules on CR operations. As seen above the rules are primary dependent on whether it's a co- channel or adjacent channel. In section 3.1, how the White Space varies depending on the restrictions put on operation rules were shown. These restrictions are elaborated in this section.

Co-channel :

As mentioned both regulators have decided that all unlicensed secondary devices are prohibited to operate within co-channel TV station contours. They may operate using the co-channel outside the contour if they are located at a distance that is in alignment with C/I ratios defined for co-channel interference. In figure 3.1 this was described at the protection area.

For instance using the separation distance found in table 3.3 calculated by FCC a high power- fixed device with an antenna height of 30 meters may use the co-channel when the separation distance is 14 km.

Adjacent channel :

For both regulators high power CR devices are not allowed to operate within TV station contour using adjacent channels. They are both open to change this rule in the future if there is a method of making sure the licensed services are protected.

Portable devices are allowed to operate using adjacent channel if the transmit power are reduced. FCC has set the restriction to 40 mW for adjacent channel usage and Ofcom set this level to 2.5 mW.

Separation distances for co-channel and adjacent channels

FCC has calculated separation distances for different Cognitve Radio transmitter heights by using C/I defined in table 3.3. A CR device with a transmit power of 4 Watt have to be located between 6- 14.4 km away from the edge of the service area to be able to use the co-channel and between 0.1- 0.74 km to reuse the adjacent channel without causing any interference to possible TV receiver within the service area.

Antenna height of unlicensed device	Required separation (km) from digital or analog TV (full service or low power) protected contour	
	Co -channel (km)	Adjacent channel (km)
Less than 3 meters	6.0	0.1
3–Less than 10 meters	8.0	0.1
10–30 meters	14.4	0.74

Figure 3.3: Required separation distance defined by FCC [13]

Discussion

The co-channel as mentioned is denied reused within the service area and this is a rule that is not under any evalution.

The adjacent channel restriction for fixed devices is a rule FCC are open to change in the future if there is a method of making sure the licensed services are protected. Ofcom agree on this choice.

The restriction is mainly put because of the unpredictable variation that can cause actual signal levels to vary from the predicted signal levels.

By registering the TV receiver one could eliminate this problem. For instance if there is a registered TV receiver at a location, the minimum protection can be given regardless of the predicted signal level at that location. Knowing where the receivers are will make it safe to use fixed devices operating on co-channel and adjacent channels.

Summary

In this section I have reviewed the parameters put for the database and the rules regarding the unlicensed device and which channel that can be used by the CR device.

First the unused frequencies given through the TX database and the RX database was separated and the definition of Gray Space was made.

As seen there is much work in progress both in US, UK and Europe regarding White Space and the secondary utilization of the TV broadcasting band. US have been the country that has come furthest in laying criteria's for the database parameters. In this thesis the focus is the TV broadcasting band in Norway where the system uses a 8 MHz band for TV transmission. There is little work in Norway regarding the database and therefore parameters defined by Ofcom will be used. This is chosen because the channel plan in UK is similar to the channel plan in Norway using 8 MHz transmission band.

- Ofcom defined the minimum fieldstrength at the TV receiver as $50 dB\mu V/m$

- The co-channel interference ratio is 33 dB

- The adjacent channel interference ratio is -17 dB

In addition I have gone through the uncertainties that may appear when basing the protection given by the database on propagation models.

4 TV receiver registration

4.1 Introduction

In the preview chapter the TX database is presented and her the RX database are explained further.

4.2 Overview

In this chapter a overview of the parameters needed to protect TV receivers will be evaluated. These variables are important to know to be able to make a choice on what needs to be registered to protect the TV receivers. First the method is explained, and the justification for using this method and possible application scenarios are discussed.

4.3 Description of the concept

When registering TV- transmitter parameters all locations of possible user locations within the service areas of a given TV- transmitter are protected. This method is conservative regarding utilizing frequencies, it protects all locations within an area without considering if there is anyone to protect. TV receivers are not located everywhere within a service area, thus making this method ineffective especially in rural areas.

Figure 4.2 shows the population density of Norway in year 2008, the map is retrieved from SSB. Focusing on an area as in figure 4.2, the illustration shows a TV-transmitter represented by a blue triangular and a circle representing the service area. Within the service area we can see the population density. We know that:

> - Of the total population only a portion uses the digital terrestrial television,section 5.2. The RX database will protect only those using the TV service. When using the TX database those who are not using the TV service is also protected.

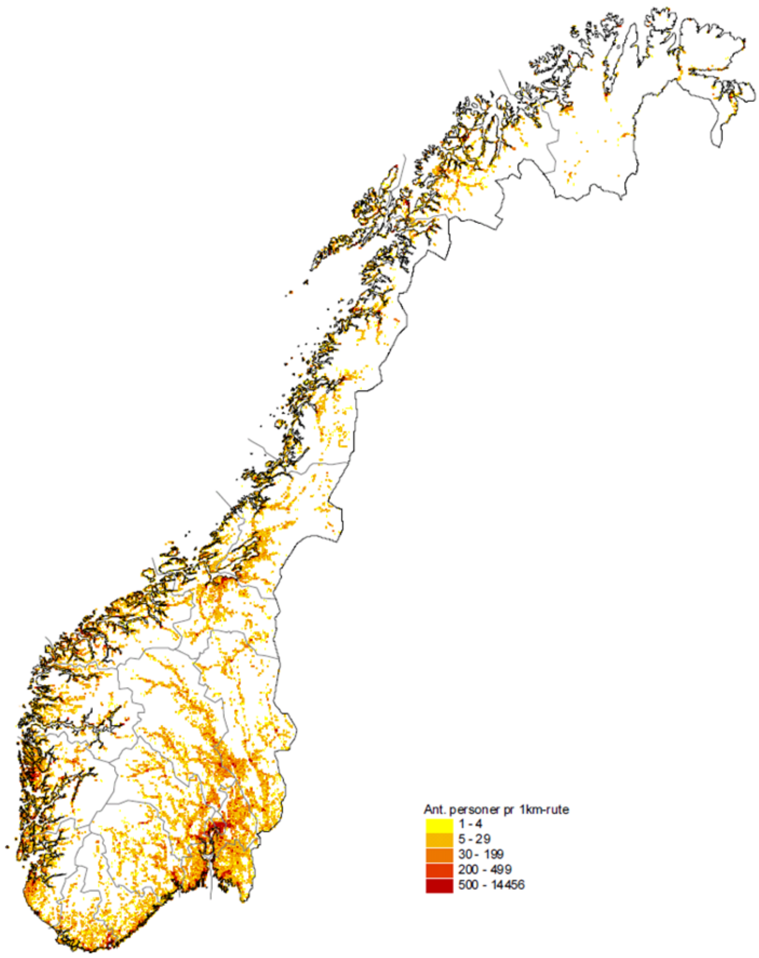


Figure 4.1: Population density in Norway for 2008, based on information from SSB

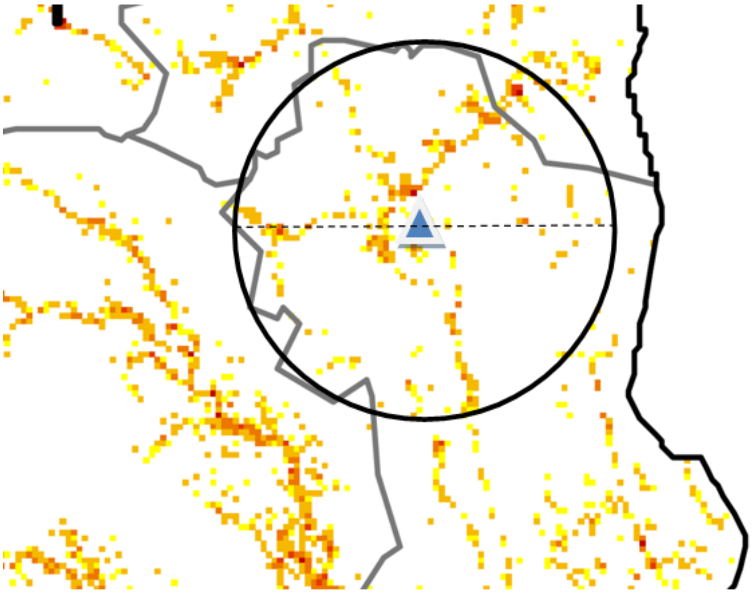


Figure 4.2: Illustation of a Tv service area at a location in Norway

- There may be households within the service area that are receiving signals from other TV stations using a different frequency. Using the TX database gives no options of adjusting the protection to fit certain cases.

- TV -coverage areas may overlap which makes it hard to make a statement regarding which channels are used at a location. Using the TX database may lead to locations intersecting with several TV service areas, which will increase the overprotection. Using the RX database the right locations and channels to be protected is found.

- In addition signal strength of the TV transmitter will vary within a service area; there are locations that do not have access to the service or were the probability of service is low because of terrain and structure. For instance 6000 households in Norway can not receive the TV broadcasting service throught regular means like terrestrial , satelitt or cabel[section 5.2]. There are no need of protecting those areas within the service area. The RX database opens up the possibility of using the frequencies at such areas for other services.

By using TV receiver information the RX database will limit the protection to those who really needs the protection. All others are not protected thus the frequency at those locations are free to be used by other systems.

In addition the method opens up the possibility of exploiting terrain and population information:

Population:

The overprotection made by the TX database will vary depending on the amount of TV receivers: In rural area were the population density is lower, the amount of locations where a channel is unused increases. The RX database is capable of giving a better mapping of the available channels by taking into account the TV receiver locations.

Exploit terrain variation:

In a country with varying terrain, where mountains and valleys are frequent the reception may vary significantly. This results in co-channels being unused at certain locations within a service area. If the receiver location is combined with terrain information one can find locations that are less exposed of causing interference to licensed users.

An example of a scenario were terrain information plays a significant role is shown. Figure 4.3 illustrates a terrain profile with a TV station and corresponding TV receivers, represented as vertical lines. There is a valley within the service area of the TV station. The TV base station is transmitting using frequency *f1* and protection is given to all the antennas on the horizontal line. In this example there are no households located in the valley, thus the frequency is not used. If one could guaranty no interference to registered receivers, cognitive systems at those areas could reuse those frequency.

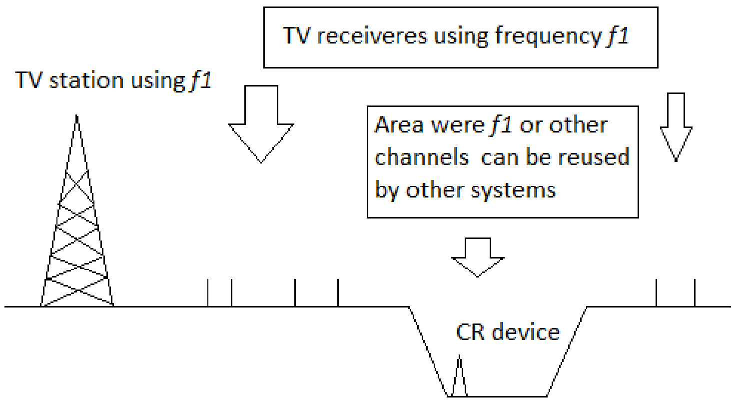


Figure 4.3: Possible scenario based on terrain information

This is a field that must be studied further; specially co-channel utilization because of interference risks. The example is sufficient to show how the registration of TV-receivers may be a benefit and the scenarios that may occur.

4.3.1 Summary

The main difference using the database is as explained the protection of users and the opening up more frequencies, especially within the service area. This method opens up for secondary systems, portable or fixed, using adjacent and co-channels within a service area.

There may still be a restriction on adjacent channel and co-channel utilization, with an emphasis on the latter. More research is needed on that field. But combining terrain information, receiver location and signal strength may ease these limitations.

In the introduction it was mentioned that the TX database makes an overprotection when protecting the whole service area. All the points presented in the above section strenghtens my statement. By protecting the whole service area one is not taking full advantage of the spectrum.

4.4 Method used for TV receiver registration

Today there is no simple way of registering TV receivers, one solution would be to have manual registration of the TV receiver by the specific household. But this can be difficult to implement. In this thesis it is assumed that all TV receivers have an IP connection and that the variables needed can be supplied using this connection.

Alternatively, user interaction can be used to register the RX positions, assuming that all TVs communicate with the mobile phone of their users or the house infrastructure. But this is not the focus of this work, as I concentrate on the benefit and effect of the RX database.

The protection of a site will be made possible by using the supplied variables and meeting the criteria put for the C/I ratio. Which will result in an area surrounding the TV receiver, were a Cognitive Radio is not allowed to operate, much like the method in section 3.5. But her the protection is granted to receiver sites rather than the service area.

- It should be noted that the method in this thesis takes to account fixed TV receivers, but there are portable TV receivers within the topology that will be interfered if not registered. Portable receivers may be a PC which can easily use the internet connection to deliver its usage, but the convenience of the static TV receiver lakes, thus further research on the protection of portable devices is needed.

4.5 TV receiver protection

In chapter 2, it was seen that to protect the TV receiver one must find the TV signal strenght at the TV receiver, in addition the geographical location must be known and which frequency it operates on. In the next subsection typical values for the TV receiver is presented and values chosen for the thesis are evaluated.

4.5.1 Signal strength

Signal strength is predicted using propagation models and it varies within the service area. It depends on how fare the TV receiver is located from the TV- station and also on buildings, structure and terrain in the area. As discussed in section 3.3.3 the predicted signal strength may differ from the actual signal strength.

Calculating the signal strength using propagations models may not be reliable for the purpose of this thesis because of the uncertainty of actual signal strength at the TV antenna receiver.

The conservative choice would be to assume the lowest possible signal strength that a receiver must have to be given service such that the users are guarantied protection, even if the calculated signal is wrong.

According to Ofcom the minimum field strength needed at the TV receiver is $50dB\mu V/m$, as mentioned this is the value used further.

4.5.2 Frequency

For a given TV receiver we must retrieve information on the frequencies used at that position. The frequencies available at a location is a field much worked on, and is also found in public records. This is further discussed in section 5.3.

For instance in Vinje a municipal in Norway the channels 25, 27, 32, 35 and 42 are used to transmit the TV service, according to Norges Televsion(NTV). The channels are found in the frequency range of 470 -790 MHz. For the simulation, instead of the frequencies available at a location the corresponding channels are used.

4.5.3 Position

Being able to locate the position of TV receivers is important when protecting TV receivers. For the TV receiver to be given protection the geographical position of the

TV receiver must be decided for a given margin. Today, there is no such information. The approach chosen in this thesis is to register household locations. TV- receivers are located inside houses, which makes it possible to use an address to locate a TV receiver.

We know that not every household has a TV receiver. In addition not every household uses terrestrial television, some use the satellite transmission or cable to get access to TV services[chap 5]. Thus, within a TV service area there are households that are not in need of protection. For the implementation in chapter 7 and 8 a statistical approach is used. Statistics on the usage of the TV broadcasting system is used to find the households, the method is explained further in chapter 5.

Accuracy of positioning

The accuracy of the TV receiver position is hard to specify when using address as the locater. There are two situations to be aware of.

First, while the address will be located as a point in a map, the actual receiver antenna may be a distance away. An address will not give the exact geographical location of a TV receiver antenna, thus one must take into account a margin of error of some meters. This margin can depend on the building size and the size of the estate.

For instance in a complex, regardless of the amount of flats, the antenna may be located at the top of the roof and the residences may receive the TV service using a cable connected to the antenna anywhere within the building. The best way to protect the users would be to protect the whole building from interference. Let's assume a regular household occupies an area of 10x10 meter. Thus, there may be a margin of error of 10 meter, depending on were the TV antenna is located. An estate may occupy a larger area, thus the margin of error will increases. In this thesis it is assumed that regular households with a size of 10x10 meter are found at the areas evaluated.

Secondly, a map is a representation of a physical area and depending on the object that is pinpointed on a map there will be a deviation by some meters. In Norway the most accurate information that a map may be based on will have an error of margin of +/- 2 meters depending on the object [27].

For the example presented the total margin of error is in the order of 10 m when using an address to locate a TV receiver. The importance of the error depends on how spesific one needs the data to be. For the simulation, the population density is represented in grids and is not based on the spesific household address. Thus, this aspect can then be ignored.

5 Scenario

5.1 Introduction

In previews chapters I have investigated registration of TV transmitters and also an introduction on how the registration of TV receivers will be done.

In this chapter I will present how the remaining objectives of this thesis will be examined.

- Which is to analyze the amount of unused location and the potential Gray Space Amount. The knowledge level were mentioned in the introduction:

    1) KN1. Knowing the position of TV receivers and the possible available channels

    2) KN2. Knowing the position of TV receivers and broadcaster information

    3) KN3. Knowing the position of TV receivers and channel usage on a hourly basis

- In addition the result is evaluated for different Cognitive radio devices.

In the next section the TV broadcasting system and possible amount of Gray Space in Norway is presented. The information is used to define the knowledge levels. In the last section the method used to retrieve the result and a detailed overview of the tasks done in this thesis is reviewed.

5.2 TV broadcasting in Norway

Before explaining the method used in this thesis, the system in Norway is reviewed and findings are used to define some of the variables used in the simulations.

5.2.1 Technology

The TV broadcasting service is a broad name for a wide range of technologies. It may be analog or digital. In Norway a digital broadcasting service using the Digital Video broadcasting (DVB) standard is applied [28]. This system may be distributed through cable, satellite, or terrestrial. In addition the TV-service is given through fiber [16].

A TV receiver may use one or more of these technologies to get access to the TV-service. In this thesis the focus is on users using the digital terrestrial television (DDT) system.

5.2.2 License

The digital terrestrial television is operated by NTV, who has the license for the development and operation of the digital terrestrial television in the frequency range between 470 to 790 MHz [29] (ch. 21- 60). The company is owned by NRK, RiksTV and TV2.

The 320 MHz spectrum is split in channels ranging from 21-60, each having a bandwidth of 8 MHz.

A TV channel is distributed through a Multiplex(MUX). The MUX is an entity that can contain several TV channels, but only occupies one of the 21-60 channels in the spectrum [30].

5.2.3 Network capacity

NTV rents out network capacity to NRK and RiksTV in Norway [30]. RiksTV offers pay-TV to customers while NRK is obliged to offer public broadcasting for free. TV2 is managed by RiksTV [31]. NRK, local- TV and other free channels may also be received through RiksTV without paying extra [32].

According to the the final act RCC-06 Norway is given 7 MUX'es, today 5 MUX are in use. MUX 1 is used to distribute NRK channels, MUX 2 is used for TV 2 channels and distributed through RiksTV, and RiksTV is given MUX 3-5 for their own channels, se table 5.1 .

Thus, a total of 40 MHz of the total 320 MHz is used for TV service.

Table 5.1: Multiplex(MUX) usage in Norway [30]

MUX 1	**MUX 2**	**MUX 3**	**MUX 4**	**MUX 5**
NRK 1 HD	TV 2 HD	TV Norge HD	Disney Channel	TV 2 Sport2
NRK2	TV 2 Filmkanaler	National Geographic	Discovery	TV 2 Sport3
NRK3	TV 2 Zebra	FEM	Animal Planet	TV 2 Sport4
NRK radiokanaler	TV 2 Nyhetskanal	BBC World News	TV3	TV 2 Sport5
	TV 2 Sport1	Eurosport	Viasat 4	TV 2 Premier League 2
	TV 2 Sport	LokalTV	Canal + First	Visjon Norge
	Premier League HD	Frikanalen	Canal + Hits	The Voice
		P4	Canal + Fotball	SVT 1
		RadioNorge	TLC Norge	SVT 2
		Radio 1	Max	Disney XD
		TV 2 Bliss		Playhouse Disney

5.2.4 TV service receiver

A household owning a TV must pay a television license fee which funds the public broadcasting from NRK. NRK is also distributed through RiksTV. To get all other channels customers must subscribe to RiksTV [33, 32].

For the knowledge level to be implemented we must know the number of households receiving the TV service using the DTT, the costumer basis of the broadcaster can be used to find this variable.

Through NRK's homepage it is found that per 2009 there were 1.8 mill households paying the NRK license fee. RiksTV has a customer basis of 500 000 households in 2010.

5.2.5 Coverage

In Norway the Norwegian Post and Telecommunications Authority (NPT) has put a requirement that 98 % of the households and 87 % of cottages and leisure homes must have access to the DTT service [29]. This is covered using ca. 430 transmitters.

Locations that do not have access to the digital terrestrial system will get access through other distribution forms. Thus at those locations the MUX'es are not used.

5.2.6 Evaluation

Using the information from above sections it is assumed that:

- Though 98 % have access to the terrestrial service there is no public knowledge on how many within an area is actually using the service and were they are located. NRK and RiksTV have information on their licensees. But this information is business sensitive. But the amount of people using the service is less then the amount that has access to the service.

- The amount of MUX'es occupied at a location may vary from 1 to all 5 MUX's. In some areas there is a lack of access to any MUX.

- It is assumed that all 5 MUX'es have coverage of approximately 98 % coverage. Thus at 98 % of the households all MUX'es are available. This assumption may be wrong at some locations. For instance depending on the frequencies occupied by the MUX, the reception at the edge of a service area may vary [34].

- Locations that do not have access to the digital terrestrial TV or were there are no TV receivers are assumed as location were the MUX'es are possibly vacant.

5.3 White space amount in Norway

5.3.1 Finding Gray Space amount in Norway

The TV broadcasting band consist of 320 MHz spectrum, and as mentioned in the last chapter the occupied number of frequency is, 5 MUX'es x 8 MHz= 40 MHz. Thus, there is a theoretical maximum amount of 280MHz Gray Space at the locations where the TV service is available.

The channel used for a given MUX will change depending on the area evaluated. Therefore an evaluation on what channel that contains Gray Space must be done for each area. For instance MUX 1 can use channel 21(470- 478 MHz band) in one city and 35(582-590 MHz band) in another. This information is available in public records [29].

In addition the actual amount that can be used will vary depending on restrictions put on the channel usage and the CR device [3.2.2].

Thus to find the specific channel available at a location, an analysis on a CR device and which MUX are used to distribute TV channel in the area must done.

In the upcoming sections the knowledge levels and how they are implemented in this thesis is explained.

5.3.2 Knowledge level 1: Depending on TV receiver location

From chapter 2 we know that a TV service area is protected, regardless if the TV service is used or not. One could decrease the areas given protection by using detailed information on TV receiver locations, thus locally unused channel within the service area may be accounted for. This will then increase the amount of locations where a MUX is referred to as unused.

Knowledge level 1 is defined as having information on TV receiver locations but no information on the actual channel usage.

We know that between 1- 5 MUX'es are available at the TV receiver locations. The worst case scenario is to assume that all 5 MUX'es are used within a service area, this is used for knowledge level 1.

In chapter 4 it is assumed that the TV receiver locations are found through an IP connection. But for the simulation, information retrieved from SSB is used to find locations on the TV receivers.

5.3.3 Knowledge level 2: Depending on broadcaster information

Further rather than assuming that a MUX is used and therefore protected , one could increase the Gray Space if detailed information on the actual channel usage at each TV receiver could be retrieved.

Knowledge level 2 is defined as knowing the TV receiver locations and knowing which broadcaster a TV receiver subscribes to.

Discussion

Which broadcaster the household/user subscribes to will decide the MUX usage at that location. For instance NRK users will use MUX 1 as seen in table 5.1.

Finding the location were a MUX is used may be difficult to retrieve but a statistical approach is used and explained in the chapter 7. The amount of households receiving a MUX is calculated here using the total amount of subscribers per broadcaster in comparison to the total amount of households in Norway.

There are accourding to SSB approximately 2 million households in Norway and we know that 98 % of the households have TV coverage. In addition the terrestrial television receivers are either RIKSTV or NRK costumers[section 5.2].

We know from table 5.1 that NRK is distributed using MUX 1 and RiksTV uses MUX 3, 4, 5. MUX 2 is used for TV2 channels. It is concluded that:

- 1.8 million households paid for the NRK license in 2009, this is approximately 90 % of the household in Norway. There may be TV receivers that are not registered because they haven't paid the license fee though it is required. Because of the uncertainty 98 % is used rather than 90 %. Thus all households receiving TV service are assumed as having access to the NRK channel.
- Through RiksTV website it is found that they have a subscriber basis of 450000 per 2010, but only 300000 are paying subscribers. The number of households receiving RiksTV is calculated to 15 % of total households.
- TV2 is distributed to approximately 97, 9 % of the households but this number included all platforms: Cable, satellite, DTT. TV2 has gone from a public free channel to a pay TV and it is therefore hard to find they're costumer basis using the DTT, at this point. But according to TV2 they're channels are distributed through RiksTV [31]. Thus, for further analysis information on TV2 users and RiksTV users are integrated.

Table 5.2: Knowledge level 2: Channel usage

MUX	**Broadcaster**	**Percent**
NRK	MUX 1	98 %
RiksTV and TV2	MUX 2,3,4,5	15 %

5.3.4 Knowledge level 3: Depending on usage on a hourly basis

According to “Norsk mediabarometer“ from 2010 ,TV is watched on average 2 hours and 32 min a day [35]. This is a major underutilization of a channel available 24 hours a day. If we have knowledge on what time the different MUX'es are used, one could further increase the available Gray Space.

Knowledge level 3 assumes knowledge on location, channel and on what time the channel is used.

If information on when the TV is used is given through the IP connection assumed in chapter 4, one could find Gray Space amount on a dynamically basis. TV usage activity must be retrieved to be able to simulate this.

TV viewing

In Norway, both TNS Gallup and SSB analysis the TV usage in Norway using different methods.

Through media Norge's homepage average amount of time a channel is watched is found for different time period per person. This information is used as a basis for analyzing the amount of households watching a channel for a given time- period.

The information is based on data from TNS Gallup who collects their information by analyzing the result from digital boxes located at 1000 household that represent the variety of homes in Norway. Table 5.1 shows the market share for TV channel in 2009 at different time periods [36].

The information is used to characterize the channel usage in time for a given MUX. The method chosen to find the MUX percentage, is by summarizing the marked share of the TV channels that are transmitted using a MUX.

For instance according to table 5.1, TV channels NRK 1, NRK 2 and NRK 3 are transmitted through MUX 1. Thus, the sum of the marked share for time: 06:00- 09:00 is summarized and put equal to 29.6 %. This time- period is referred to as time-period 1.

Table 5.3: Information on the markedshare for timeperiod: 06:00- 09:00, 20:00- 23:00

Channels distributed through:	**Time period 1**	**Time period 2**
MUX 1	29.6 %	41.9 %
MUX 3(and 2)	3 %	10.4%
MUx 4(and 5)	4.7 %	9.6 %

The statistics for each MUX does not contain the entire list of channels found in the given MUX. For instance, MUX 1 has a marked share of 29.6 % at time-period (06:00- 09:00), but the number is only based on 3 channels. Likewise, MUX 3 is based on TVNorge and Fem, and MUX 4 is based on Viasat 4 and TV3. The marked share of MUX 5 can't be retrieved using the table, because no channels transmitted through MUX 5 are found in the table from TNS Gallup.

Since there are some uncertainties on the amount of receivers using MUX 2 discussed in section 5.3.3, and because the marked share of MUX 5 is hard to specify, only statistics for MUX 1, 3, and 4 are used. But to be able to do a total analysis of all the MUX'es, MUX 2 and MUX 5 is integrated with the results of MUX 3 and 4, respectively.

It is assumed that there are more households watching TV 2/MUX 2 channels than MUX 5 channels. For instance using the table, TV 2 has a marked share of 32,3 % for time- period 1, while the value for MUX 5 is not defined. But it is assumed less than the marked share for MUX 4.

For Knowledge level 2, MUX 2 was integrated with the MUX'es used by RiksTV, to be consistent with the method used MUX 2 will be evaluated together with values from either MUX 3 or MUX 4. According to TNS Gallups homepage the most activity is assumed at time- period 20:00- 23:00. At this time MUX3 will have the highest marked share of 10. 4 percent compared to the 9.6 percent marked share for MUX 4 . The difference is not much, but based on the discussion MUX 2 and MUX 3 will be evaluated together using the mare share for MUX 3. And MUX 5 will be evaluated using the marked share for MUX 4.

In the simulation two time period are chosen and evaluated; 06:00- 09:00, 20:00- 23:00, referred to as time period 1 and time period 2. The information from Media Norge below is used to define the table 5.3. Time -period 1 is considered the time- period with lowest marked share, considering MUX 1 example above. And Time- period 2 is as mentioned the time with highest TV activity. Those time- period together are assumed sufficient to represent how the activity varies throughout the day.

TNS Gallup: Markedsandeler for ulike tidsperioder 2009, fordelt på alle (prosent)

Ar	Alle	Tidsrom	NRK1	NRK2	NRK3	TV2	TV2 Zebra	TV2 Nyhet	TV2 Film	TVN	FEM	TV3	Viasat4	Andre	Totalt
2009	Alle 12+ år	0600-0900	20,8	2,2	6,6	32,3	0,7	6,8	0,5	2,2	0,8	2,6	2,1	22,4	100,0
	Alle 12+ år	0900-1500	29,6	3,1	2,6	19,0	2,1	3,8	0,8	5,7	2,6	6,2	4,0	20,5	100,0
	Alle 12+ år	1500-1830	21,3	6,3	3,1	19,9	4,0	2,7	0,8	7,6	2,4	7,2	4,3	20,4	100,0
	Alle 12+ år	1830-2000	45,2	3,4	2,1	22,0	4,4	0,8	0,4	4,4	1,3	4,2	3,3	8,5	100,0
	Alle 12+ år	2000-2300	35,2	3,7	3,0	25,3	2,7	0,8	0,6	8,6	1,8	6,7	2,9	8,7	100,0
	Alle 12+ år	2300-0200	26,7	4,5	3,7	17,8	3,4	1,5	1,5	9,8	2,6	7,8	4,3	16,4	100,0
	Alle 12+ år	Døgn	31,9	4,1	3,0	22,1	3,2	1,8	0,8	7,5	2,0	6,5	3,6	13,5	100,0

Figure 5.1: The table show the average markedshare for the year 2009; TV viewing per person for a given time-period, [36]

Note:

- In a real system, real-time information one the channel usage must be retrieved. This is not possible as the system is today.

- The information found is based on the time usage of a person at age 12 +. Thus is not per household.

- The information is not specific for the terrestrial TV.

- The information found in the table does not contain all TV channels, thus only the TV channel statistic for the TV channels found in the table is used.

- The information is based on an average markedshare for the year 2009.

Some of the limitation of the information may lead to minor errors in the statistics used, but is not critical. The purpose is to show that the locations containing unused frequencies increase when the TV viewing time is taken to account.

5.4 Detailed tasks of the thesis

5.4.1 Introduction

To be able to analyze the amount of unused frequencies with focus on the the Gray Space, one must first find the amount of locations containing unused frequencies- referred to as unused locations.

Three areas in Norway are chosen to be analyzed. For each knowledge level the amount of locations containing Gray Space is found when changing the protection degree. In the next section the method used is presented.

5.4.2 Method

For the areas evaluated we need information on:

- TV transmitter information, which is used to retrieve a list of channels available at a location
- TV receiver information, such that protection is given at the TV location. The information needed are reviewed in chapter 4.

Using TV receiver locations and combining it with channel usage of each TV receiver, one can retrieve information on the amount of unused locations.

To find out if the unused frequencies can be used by a CR device, an evaluation must be done for each CR device type. In the introduction it was mentioned that a 4 W fixed and a 100 mW portable device are evaluated.

The analysis of locations containing Gray Space can be done in different ways. In this thesis to elements are varied: *Knowledge level* and *protection degree*.

Knowledge levels

The channel information for each knowledge level is referred to as:

- Knowing the possible channel usage, correspond to knowledge level 1
- Knowing actual channel usage, correspond to knowledge level 2
- Knowing channel usage based on time, correspond to knowledge level 3

For a given channel usage the locations of TV antennas receiving the channel are registered. The amount of location unused locations are analyzed when the level of knowledge is changed.

Protection degree

A Cognitive radio (CR) must be evaluated at the unused locations before making decision on whether the frequencies can be utilized by the CR device. For a given CR device there are requirement on the distance between the CR and TV antenna, as mentioned in section 3.5.2. The Gray Space amount will vary depending on this distance.

This distance will have a corresponding protection degree, the method used to define the protection degree is presented in chapter 7.

For instance a CR device with EIRP of 4 Watt is calculated to have a protection degree of N= 15 when using a grid size of 1km x 1km.

The degree of protection or the size of the protection needed for a 4 Watt and a 100 mW CR device is calculated in chapter 6.

5.4.3 Simulation method

The method is simulated using matlab and in chapter 7 the method will be described further using a test case. The test case will be implemented using a 20x20 matrix, and how the matlab is used to reach the goals of this thesis is explained.

- The first analysis is interesting because it shows the amount of locations that contain unused frequencies and how this amount changes in accordance to the increase in information. In addition the result backs the claim which was done in chapter 3, where it was said that the TX database makes an overestimation when protecting all locations within a service area.
- The second analysis is interesting to be able to see the practical value of the TV registration. The value is found when it can be shown that other systems may operate at those locations and utilize the unused frequencies.

It is expected that when the amount of knowledge increases, the amount of usable unused frequency also increases. It is interesting to find out how much this amount is increased when the information level changes between the knowledge levels: from knowing the TV receiver location and the possible channel usage, to knowing which broadcaster a receiver is subscribing to, and finally if we in addition know when a channel is used in time.

This amount will depend on the CR device, less for high power CR devices and greater for low power devices.

The largest difference between registering TV transmitter information and receiver information is seen in the amount of Gray Space found within the service area of a TV station.

6 CR device parameters

6.1 Introduction

In this chapter the maximum range of the CR device with varying transmitter power is calculated, this is later used to give a better understanding on the result of the simulation.

6.2 Cognitive radio device

In the introduction it was mentioned that the Cognitive radio devices usually are separated in two categories; fixed and portable. It was also mentioned that the evaluated devices are both a fixed 4 W device and a portable 100mW Cognitive device. The 4 W fixed device represent a IEEE 802.22, while the 100 mW represent a portable device used both for in- home applications and applications used outdoor. The protection needed surrounding a TV receiver is calculated in this section.

The protection distance is defined by the min. distance needed between the CR device and the TV receiver, this is calculated using co-channel and adjacent channel interference ratios. Figure 6.1 illustrates the values calculated in this chapter.

6.3 Maximum range

From chapter 2 we know that the required S/I will put a limit on E_{rCR}= the maximum signal strength transmitted by the cognitive radio measured at the TV receiver site, which will determine the CR transmitter range.

Maximum range is found when the fieldstrength at the site of the CR device,E_{tCR}, reaches E_{rCR}.

$$L_{max} = E_{tCR}[dB\mu V/m] - E_{rCR}[dB\mu V/m] \tag{6.1}$$

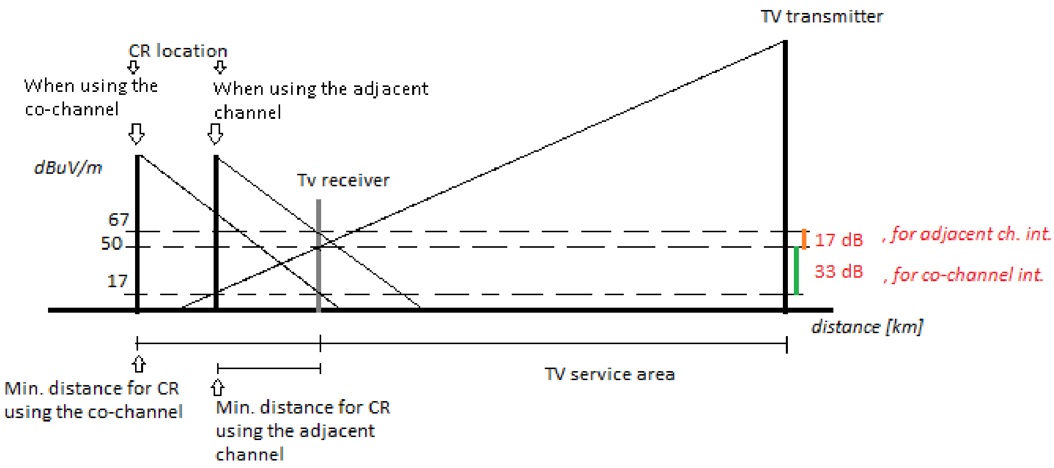


Figure 6.1: Illustration of the variables affecting the min. distance when considering co-channel and adjacent channel interference ratio

Using a chosen propagation model the maximum distance can be determined using the variable max pathloss L_{max}. For a given CR transmit power, P_{tcr}, equivalent threshold in terms of field strength at the CR transmitter site must then be calculated.

The max allowed EIRP is converted to dBm and then the field strenght is found using equation [37]:

$$E[dBuV/m] = EIRP[dBm] - 20 * log_{10}(d[m]) + 104.8 \tag{6.2}$$

Where:

d, is the distance where the fieldstrength is measured. In this thesis is chosen to be d=1 m.

EIRP[dBm], Equivalent isotropically radiated power(dBm)

$$EIRP[dBm] = 10Log10 * (mW) \tag{6.3}$$

For instance the fixed device with 4 W EIRP will have corresponding value of EIRP[dBm] = 20 dBm and a fieldstrength of 140.8 $dB\mu V/m$. The 100 mW device will have corresponding EIRP[dBm] = 36 dBm and a fieldstrength of 124.8 $dB\mu V/m$.

6.4 Max allowed CR field strenght at TV receiver

In section 3.5 the minimum field strength and protection criterias for the TV broadcasting band in UK was reviewed.

- The DVB-T service has a E_{rtv}= minimum fieldstrenght of $50dB\mu V/m$. This is the field strength equivalent of P_{rtv}
- The requirement for the S/I ratio for a $8MHz$ band is $33dB$ for co-channel and $-17dB$ for adjacent channel usage.

In chapter 2 it was seen that the required S/I decides the allowed CR power level at the TV receiver. In this thesis the allowed CR level is calculated in fieldstrength. Thus, max allowed CR field strenght, E_{rcr}, at the TV antenna is:

$$E_{rcr} = E_{rtv} - S/I \tag{6.4}$$

When substituting for the values chosen we get E_{rcrCO}= the fieldstrength for the co-channel usage and E_{rcrAD} for the fieldstrength considering adjacent channel usage :

$$E_{rcrCO} = 50dB\mu V/m - 33dB = 17dB\mu V/m, \text{ for co-channel usage} \tag{6.5}$$

$$E_{rcrAD} = 50dB\mu V/m - (-17dB) = 67dB\mu V/m, \text{ for adjacent channel usage} \tag{6.6}$$

To calculate the corresponding range of a CR device, a propagation model must be chosen.

6.5 Propagation loss between CR device and TV receiver

The propagation loss model is calculated between the CR transmitter and the TV receiver. The model is used to calculate the interference that is inflicted on the TV antenna.

In this thesis both Okumura- Hata propagation model and Free space model are used to represent the propagation loss between the CR transmitter and the TV receiver. After evaluating the values, the model that gives proper values for the Cognitive radios are chosen.

6.5.1 Free space model

The free space model assumes line- of - sight, meaning there are no obstacles in the way which is a worst case scenario [38]. The pathloss is proportional with the square of the distance between the CR transmitter and the TV antenna. The propagtion loss using the Free space model is seen in figure 6.2 and discussed in the section below.

$$FS = 20 * log10(d[km]) + 20 * log10(f[MHz]) + 32.44; \tag{6.7}$$

Where:

FS, is the Free space path loss

d, is the distance of the receiver from the CR transmitter(km)

f, is the signal frequency(MHz)

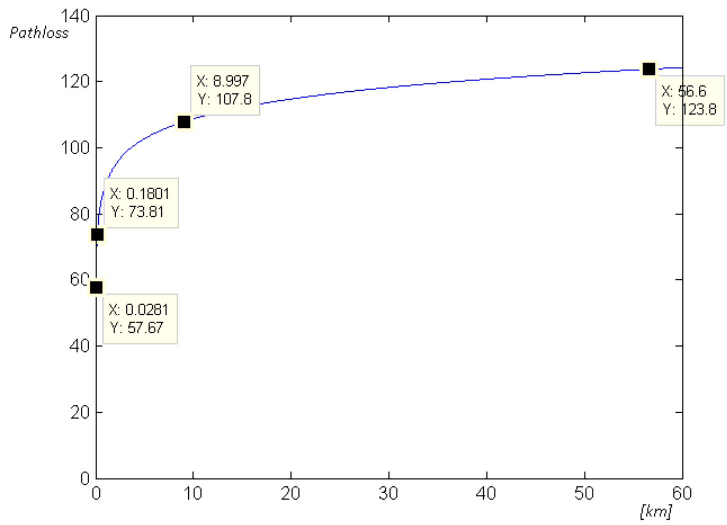


Figure 6.2: Propagation loss based on the Free space model

6.5.2 Okumura- hata propagation model

The Okumura Hata model is a radio frequency propagation model used to predict propagation loss between a base station and mobile device. The parameters of the model are fitted for three different topologies: Urban, suburban and rural [38, 39]. The model is valid for:

- *Frequency:* 150 MHz- 1500 MHz
- *Mobile height, [hm]* 1 m- 10 m
- *Base station height,[hb]:* 30m - 200m
- *Distance between device,d:* 1 - 20 km

The pathloss for suburban like environment is chosen, this is primary because the areas chosen in the simulation fits this description.

The resulting path loss per distance[km] is shown in figure 6.3. The figure includes two propagation loss curves. The upper showing the pathloss when considering a CR transmitter height(hb) of hb=30m, this represent the pathloss experienced for a 4 W fixed CR device. The lower curve is calculated using a CR transmitter height of hb=2m, which represent a 100 mW portable CR device.

As seen from the definition of the Okumura Hata model, it is not valid for a base station height less then 30m, nevertheless it is used for hb=2m. If the min. distance is underestimated as a result of using the Hata model the protection given to the TV receiver will not be sufficient. The resulting min- distance using the Okumura Hata model for hb= m is compared with other 100mW devices in the discussion in section 6.7. Based on the discussion the values calculated are considered sufficient.

$$L = 69.55 + 26.16 * log10(fc[MHz]) - 13.82 * log10(hb[m]) - a + (44.9 - 6.55 * log10(hb[m])) \tag{6.8}$$

$$* log10(d[km]) - (2 * (log10(fc[MHz]/28))^2 - 5.4)$$

$$a = (1.1 * log10(fc[MHz]) - 0.7) * hm[m] - (1.56 * log10(fc[MHz]) - 0.8) \tag{6.9}$$

where for this thesis:

L = pathloss using the Okumura hata model

fc = frequency (MHz)

hb = Base station height, where for this thesis correspond to CR transmitter heigth(m)

Table 6.1: Max range for a Cognitve radio device with 4 W EIRP, considering both free space model and Okumura Hata propagation model

4 W EIRP	P_{tcr}**[dBm]**	**CR Field strength at a distance of d= 1 m,**$E_{CR}[dB\mu V/m]$	pathloss, L $[dB]$. Depending on E_{rcrCO}=17$dB\mu V/m$ or E_{rcrAD}=67 $dB\mu V/m$	Min. distance: free space model	Mini. distance: Hata model
co-ch. adjacent ch.	36	140.8	123.8 73.8	56.6 km 180 m	7.35km 281 m

hm = Mobile height, where for this thesis correspond to the TV receiver heigth(m)

d = distance between CR transmitter and the TV receiver(km)

a = correction factor for mobile antenna height

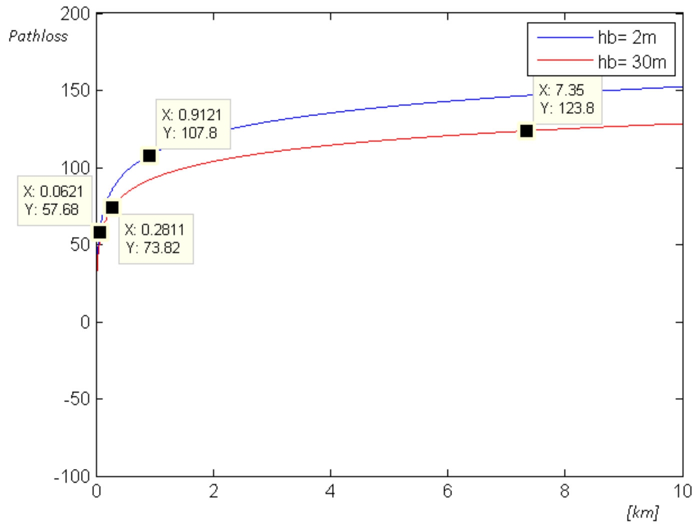


Figure 6.3: Propagation loss based on Okumura- Hata pathloss model for suburban enviroment. The upper curve shows the result when the CR transmitter height hb= 30m and the lower is the result when a hb= 2m is used.

Table 6.2: Max range for a Cognitive radio device with 100 mW, considering both free space model and Okumura Hata propagation model

100 mW	P_{tcr}**[dBm]**	**CR Field strength at a distance of d= 1 m,** $E_{CR}[dB\mu V/m]$	Pathloss, L $[dB]$. Depending on E_{rcrCO}=17$dB\mu V/m$ or E_{rcrAD}=67 $dB\mu V/m$	Min. distance: free space model	Min. distance: Hata model
co- channel adjacent ch.	20	124.8	107.8 57.8	8.99 km 28 m	910 m 62 m

6.6 Result

For the C/I requirment for co-channel and adjacent channel interference the resulting maximum range of a 4 W fixed device and 100 mW device are shown in table 6.1 and 6.2. The min. distance needed between the CR transmitter and the TV receiver are calculated using both the Free space model and the Okumura Hata model.

For a CR device to reused the co-channel or adjacent channel there has to be an area surrounding the TV recievers with a diameter corresponding to the values in the table.

Free space model:

For instance evaluating a CR device with 100mW EIRP when using the free space propagation model, which assumes a line- of -sight , there must be an area surrounding the TV receivers with a diameter of 9 km for co-channel usage and 28 m for adjacent channels. When the CR device is located outside this area it may transmit without causing interference.

For a 4 Watt CR device using the co-channel the minimum distance required is 56.6 km before it reaches the max field strength allowed at the TV receiver locations. When using the adjacent channel the distance decreases to 180 m.

Okumura Hata model:

The minimum distance needed for a 4 Watt CR device is approximately 7.35 km, when using the co-channel. When using the adjacent channel the distance is 281 m. For the low power device the distance decreases to 910 m for co-channel usage and further to 62 meter for adjacent channels.

6.7 Dicussion

Before choosing a pathloss model, the result must be evaluated:

Fixed

FCC is the only regulator that has set requirements on separation distance between a receiver and a CR device. In their calculation they consider a fixed 4 W device with varying height { 3m-30m }[Fig 3.3]. For a height of 30 m the co-channel separation distance was 14 km and 0.74 km for adjacent channel interference.

In the calculation of this chapter this compares to 56.6 km and 180 m when using the free space model, and maximum range of 7.35 km and 281 m when using the Okumura Hata model.

The free space model gives a higher value then FCC for fixed devices, while the Hata model resulted in approximately half of the value. For the adjacent channel usage both pathloss models results in lower values than the 0.74 km value calculated by FCC.

The Okumura Hata model is regarded the best choice for the fixed device. Although it underestimates the high power device and overestimates the low power device for the examples discussed.

- The differences in the values calculated between the FFC value and the min distance in this thesis are a result of several factors, such as propagation model used, frequency range evaluated and so on. In US the TV broadcasting band transmits using lower frequencies, thus resulting in larger range for a CR device.

Portable

There is little work regarding separation distances for portable devices using the TV band, making it hard to compare the values found.

A bluetooth device with a power of 100 mW has a 100 m range. In the introduction it was mentioned that the 100 mW portable device could represent a WLAN access point. Such an access point has different range depending on if its used inside or outside. For instance for the IEEE 802.11b the range for inside coverage is 100m and 200 m for outdoor coverage, with a data transfer speed of 11 Mbps and a typical transmit power of 20 dBm= 100mW [40].

In a addition the information from FCC for a 4 W fixed device with a CR transmitter height of 3 m can be used to verify the result. Since the separation distance for the 4 W device will be higher than the separation distance for the 100 mW device, it can be used as a good value to measurement the result retrieved for this thesis. When the 4 W transmitter height is 3 m the separation distance is 6 km for co-channel interference and 100 m for adjacent channel interference. Thus, the separation distance for a 100mW device will be lower than 6 km for co-channel and lower than 100 m for adjacent channel interference.

Considering these point, the minimum distance needed for the portable 100 mW is estimated to be between 200- 6 km for co-channel usage and approximately 100 m for adjacent channel usage. Because the values found by FCC are based on a transmitter power of 4 W, which is 400 times larger then 100mW, the result are assumed in the order of 100 rather than 1000.

Free space gives a larger range as expected for both transmit powers. Using the free space model the 100 mW coverage corresponds to 9km and 28 m. Compared to 910m and 62 meter when using Okumura Hata model. Based on the values reviewed the Okumura Hata model fits the estimated values of the min. distance needed for portable 100 mW CR devices. Even though the Okumura Hata model is not valid for the portable device were the mobil height is hb= 2m, it fits the assumed values discussed above.

Thus, based on the evaluation it is stated that the Okumura Hata model will gives the most accurate results, and is therefore chosen to represent the propagation loss between the CR device and the TV receiver.

Summary

For a fixed 4 W device the minimum distance needed between the CR device and TV receiver is:

- 7.35 km for co-channel and 281 m for adjacent channel usage.

For a portable 100mW device the corresponding result is:

- 910m for co-channel and 62 meter for adjacent channel

7 Implementation

7.1 Introduction

The two next chapters are simulations based on a testbed and real input values, respectively. The implementation is similar in many ways. Major difference lay in definition of the topology and TV receiver density. While the test case uses a statistical approach, the real simulation will use actual information at three locations in Norway. Further an analysis of channel usage for each knowledge level will be done. Specific TV receivers are chosen for each knowledge level and information on locations containing unused channels is retrieved.

This chapter will first introduce how the implemention is done using matlab.

7.2 Programming structure

The code has three building blocks;

- Defining start inputs
- Chosing TV receiver locations to be evaluated for each knowledge level
- Implementing the protection degree for each knowledge level

Then the code is run to retrieve information on locations were the available channels are unused.

For each knowledge level corresponding channels are evaluated and TV receivers using those channels are chosen. The function *protection* is called to implement the protection degrees. The amount of locations containing possible Grey Space are calcuated and found in the array *noneProtected*. The result is shown in table form and using a color map of the areas.

In chapter 5 the method to achieve the goals of this thesis was outlined in detail, the next section will describe how the method is implemented using matlab.

7.2.1 Method

The analysis is done using a matrix. Thus, the information from an area must be converted in matrix form.

TV receiver locations are marked within this matrix, surrounding elements will then represent locations that may contain locally vacant Grey Space. Before evaluating those locations, a CR device must be considered and analyzed. The protection degree is used for this purpose.

In chapter 6 it was calculated that a CR device with transmit power of 4 *W* is required a separation distance of 7.35 *km* for co-channel and 281 *m* for adjacent channel from the TV receiver. This means there must be an area surrounding the TV receiver location with a minimum radius of 7.35 *km* and 281 *m* where the CR device is not allowed to operate.

The protection degree represents this distance and is defined both as a distance(km) and an N value. This distance must be marked and protected.

All matrix elements that are not marked and that do not contain a TV receiver are referred to as "locations containing unused channels".

Protection degree

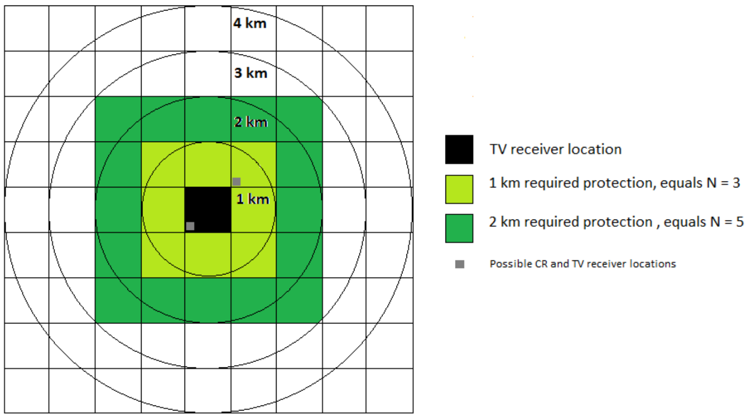


Figure 7.1: Protection degree in distance and corresponding value N

In figure 7.1 a minimum protection of 1 km and 2 km is shown. It is illustrated as circular areas surrounding the TV receiver location, where the TV receiver is illustrated as the black matrix element. The distance is measured from the nearest edge of the matrix element containing a TV receiver.

Table 7.1: Evaluated protection degrees for a 4 W and a 100 mW CR device

N values:	Co-channel	Adjacent channel
4 Watt Cognitive device	$N = 17$	$N = 3$
100mW Cognitive device	$N = 3$	$N = 3$

The matlab code converts these circular areas to quadratic NXN areas, this is illustrated as green elements in the figure. For instance a minimum protection of 1 km corresponds to a 3x3 area. The white matrix elements represent locations with unused channels. If the CR device is located at the white matrix elements it can reuse the channels that are used at the TV receiver location.

- The protection of 1 km is the minimum given, since the TV receiver can be located anywhere within the matrix element, a minimum protection of 1 km gives a protection that can vary from 1 - 2.8 km. For instance if the TV receiver is located at the lower left corner of the element, and a CR device is located diagonally as illustrated as grey quadrates in the figure. The protection of the inner circular in figure 7.1, correspond to a minimum protection of 1 km and a maximum of $2 * sqrt(1km^2 + 1km^2) = 2.8$ km, when using a 1kmx1km grid size.

Value N

The protection degree N is defined by the value equal to:

$$N = \text{round(separation distance)} * 2 + 1 \tag{7.1}$$

For the 4 Watt and 100 mW CR values the minimum distance must be converted to an NxN area to fit the matrix.

The information registered will be limited by the grid size. For instance a separation distance of 281 m will be rounded up to 1 km, because the minimum grid size is 1 km. The same must be done for the other values. This results in that 7.35 km is rounded up to 8 km and 424 m to 1 km protection. If the grid size were smaller one could get a more accurate representation.

After rounding up the separation distance one can find the protection degree N:

- $N = 8km * 2 + 1 = 17$ for co-channel

- $N = 1km * 2 + 1 = 3$ for adjacent channel

The N value for both the 4 W and the 100 mW transmit power CR device is shown in table 7.1

Based on the N values, when using 1x1 *km* grid size: the evaluated protection degrees are $N = 3, 17$ for each knowledge level. As seen the grid size results in an overestimation of the needed protection. If the grid size changes the value of N will also change. This is discussed further in chapter 9.

For the test case N = 3 and 5 is implemented.

7.2.2 Defining Start inputs

The topology is defined by the area we are analyzing. The size of this area will define the size of the NxM matrix.

In addition the matrix element size must be defined. The element size is chosen depending on the information that is available. For the test case it is not defined and for the real case it is defined by the information from SSB.

For instance Vinje is represented in a 60x64 matrix, where each element size represents a 1 kmx1km area. This will be described further for each case.

The information on TV receiver locations is used to mark certain matrix elements as TV receiver locations. The density will depend on the area evaluated. For the test case a statistic approach is done and for the real case information on population density from SSB is used. The method is described further for each case.

7.2.3 Channel usage for each knowledge level

In chapter 5 the channels for the three knowledge levels were reviewed.

For each channel level the corresponding TV receiver locations are found and marked in the matrix. The function *positionReceivers* is used for the test case and *positionReceiversReal* for the real case.

The amount of TV receivers for each level is discussed in chapter 5.3 and applied her.

TV transmitter information

Before finding out which of the TV antennas are receiving a given channel set. We must find out which channels are available at the specific areas.

For each area it is assumed that the same sets of channels are available at all locations. From section 5.2 we know that all locations have access to a maximum of 5 MUX'es.

Thus, for the test case all 5 MUX'es are assumed available within the 20x20 matrix with no further discussion on which channel those MUX'es correspond to. For the real case, information from NTV is used to find the channels that are available from the strongest TV transmitter. For instance in Vinje, the strongest transmitter is Rauland and uses channels: 25, 27, 35, 32, and 42. Those channels are assumed available at all locations within Vinje.

- This is a simplification; one could calculate the coverage area of the TV station and only take to account the TV s that based on the calculation, receives those channels. The result of the method used in this thesis is that there may be some TV receivers that are not taken to account. The amount is assumed minor when comparing to the whole topology. The assumption is made after evaluating the result from the coverage calculation program from NTV and information from NTV about SFN and their locations.

Knowledge level 1

From chapter 5.2, we know that knowledge level 1 is defined as having no information on the actual channel usage. All TV receivers within the area are assumed receives all 5 MUX'es available in the area. Thus, at those location the MUX'es are occupied.

Knowledge level 2

For actual channel usage the MUX'es for each broadcaster are separated. Thus NRK users and RiksTV users are evaluated separately. From chapter 5.2 we know that :

- MUX 1 is used by approximately 98 % of the households
- Mux 2- 5 is used by approximately 15 %.

The code is run twice to find the location where MUX 1 is unused and then where MUX 2-5 are unused.

For the first simulation 98 % of the total households within the area are chosen randomly and marked as NRK receiver locations. Then the amount of locations containing unused channel are retrieved for each protection degree.

For the second simulation 15 % are marked as RiksTV receiver locations and the unused channel are retrieved for each protection degree.

- The assumption that users are chosen randomly from the density is to my opinion a sufficient choice. The discussion of this choice is made in the evaluation in section

7.4. More appropriate information may be retrieved but is business critical for the broadcasters and thus not provided for the public eye.

Knowledge level 3

From chapter 5 we know that the MUX usage changes in time. And it was chosen two time periods, time- period 1 (06:00- 09- 000) and time -period 2 (20:00- 23:00) to simulate how the unused channel varies throughout the day. The marked share for time period 1 and 2 are found in table 5.3, for all 5 MUX'es.

For each time-period, the unused channel information is retrieved for each MUX by calling the function *timeBased* for the test case and *receiversForTimeBasedInf* for the real case. Both functions will choose the right amount of TV receivers according to the table 5.3 for each MUX.

For instance considering time period 1:

- 29,6 % of the NRK receiver location from knowledge level 2 are chosen randomly and marked as MUX 1 users at time-period 1.
- 3 % of RiksTV receiver locations are chosen randomly and marked as MUX 3 and MUX 2 users at time- period 1.
- 4.7 % of RiksTV receiver locations are chosen randomly and marked as MUX 4 and MUX 5 users at time- period 1.

For the testcase MUX 1 at time- period 1 and 2 is simulated. For the real case, all MUX are simulated.

7.3 Simulation Testcase

7.3.1 Introduction

The purpose of this chapter is to give a clear understanding on how the code will work, through a test case. It will review the scenario and describe the variables chosen for this case. The simulation is run for all knowledge levels. The main purpose of this chapter is to explain the matlab code and how to make use of the simulation result. Therefore some parameters are assumed or ignored to be explained further for the real case in chapter 8.

7.3.2 Defining Start inputs

Toplogy

The network topology is defined by(x,y). The topology in the test case is as mentioned represented using a 20 x 20 matrix.

The parameters not defined properly for the test case are:

- The size of the matrix element.

The size of the matrix element will represent a fraction of the topology. And it will depend on the format used when registering population density. It must be defined for the real case, but for the test case it is not defined.

- The topology.

The test case is represented using a 20x20 matrix but no information on how large of an area in meters or km the matrix is representing is mentioned. For the real case this will be explained and calculated to represent the three areas evaluated.

TV receivers locations

- The number of TV receiver locations within the topology is chosen to be 100.

TV receivers may be scattered with different density. For the test case, the TV receiver locations are statistically presented as being random located within the topology. The choice of 100 receiver locations and the random density is chosen as an example to show how the code will work for this scenario, and thus will not be reviewed further.

Random method

The random locations are found using two arrays, rxX and rxY, with length 100 and that for each index chooses a number randomly from 1- 20. The values in the random arrays are used as indexes for 100 TV receiver locations within the 20x20 matrix.

The random method may results in indexes that are repeated in the array, making a duplicate registration of TV receivers at the same area. Such a duplicate location is also visible in the real- world scenario. Where households and buildings can have multiple TV's.

7.3.3 Channel usage for each knowledge level

The choices made in the common section is applied her. The simulation is run for all knowledge levels. For each level different amount of receivers are analyzed and chosen randomly from the defined TV receiver locations from last section. In addition a protection degree of N = 3 and N= 5 mentioned in 7.2.1 is used. Thus for each TV receiver location, surrounding matrix elements are marked as protected.

For instance for protection degree of N= 3, 8 neighboring matrix element surrounding the TV receiver location are marked. For instance if the matrix element size represent a 1 km^2, then N= 3 would represent a protection on 1 km^2 and N= 5 will represent a protection distance of 2 km^2. Because the matrix elements size for the testcase is not defined, the corresponding protection distance is not defined for the test case.

TV transmitter information

For the test case the TV transmitter is assumed present at the center of the topology and that it transmits TV channels using 5 MUXes. All TV antennas within the topology receive one or more of these MUXes.

Knowledge level 1:Possible channel usage

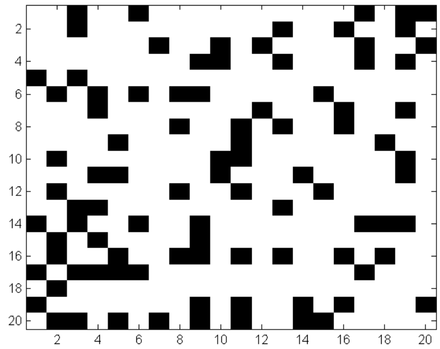
All of the 100 locations are possibly receiving all MUXes and the statistics of the unused channel locations are simulated and calculated.

The simulation result is seen in figure 7.3.3, with the input values in table 7.2 and the unused area percentage information in the table.

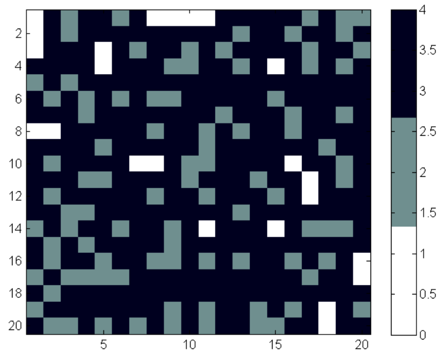
Result:

Figure 7.2 (a) shows the location of the 100 TV receivers, they are represented with black matrix elements. The other figures show the areas containing Grey Space, when the protection degree N= 3 (7.1 a) and N= 5 (7.2 b). Here the green points represents TV receiver locations, while the black area surrounding the locations is the protection area, and the white areas represent the locations containing Grey space.

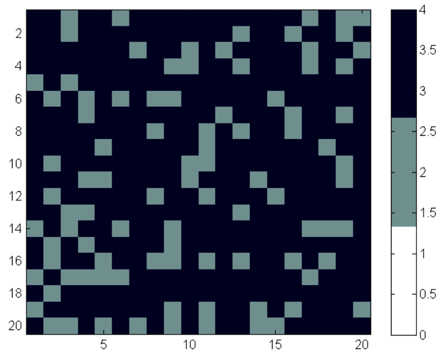
When protection distance needed between TV receiver and Cognitive radio, corresponding to protection degree N= 3 is implemented: 5.75 % of the locations in the topology are locations were the CR device could operate without causing interference. When the protection degree is N= 5, there are no locations within the topology were the CR can operate.



(a) Total amount of TV receiver locations



(b) Protection degree of N= 3, 5.75 percent



(c) Protection degree of N= 5, 0 percent

Figure 7.2: Unused locations for Knowledge level 1

Table 7.2: Percentage of population using MUX 1, 2, 3 ,4 and 5, for Knowledge level 1

	Value
Mux	1, 2,3,4,5
Presentage of population	100

Table 7.3: Result test case: unused locations for knowledge level 1

Protection degree N= 3	Protection degree N= 5
5.75 %	0 %

Knowledge level 2: Actual channel usage

A simulation is done for NRK and RiksTV channel usage. 98 % of the TV receiver locations are registered for NRK and 15 % for RiksTV, as seen in table 7.4.

Result:

98 of the TV receivers are chosen as NRK users, their location is seen in 7.3.3 (a). Figure b and c shows the unused location with a protection degree of N= 3 and N= 5.

For a protection of N= 3 there are 6.75 % unused locations were the CR can operate, but when the required protection increases the CR device can not operate within the topology- there are no usable locations were the Grey can be used.

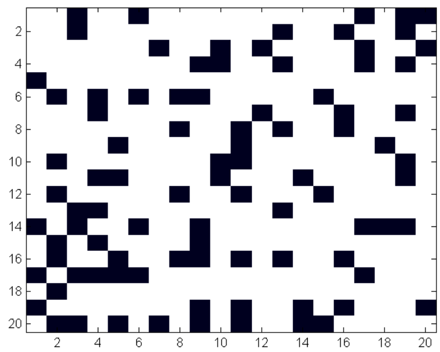
RiksTV users are found at 15 % of the TV antenna locations, thus 15 TV antenna locations are found from the total of 100 receivers within the topology, the result is shown in the table 7.6. The same protection degrees of N= 3, 5 are simulated and the amount of locations decrease from 74.25 % for N= 3, to 45% for a protection degree of N= 5.

Knowledge level 3: Channel usage based on time

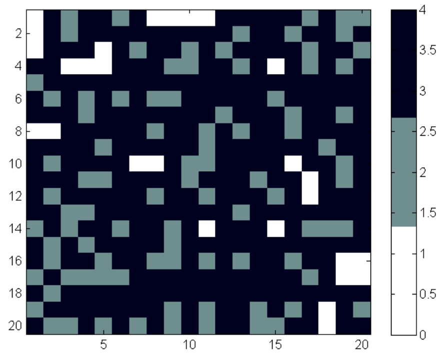
Information is retrieved from chapter 5 were the time usage has been assumed, table 5.3. For the test case only simulations for MUX 1 at time -period 1 and 2 is done.

Table 7.4: Percentage of population using MUX 1, 2, 3 ,4 and 5, for Knowledge level 2

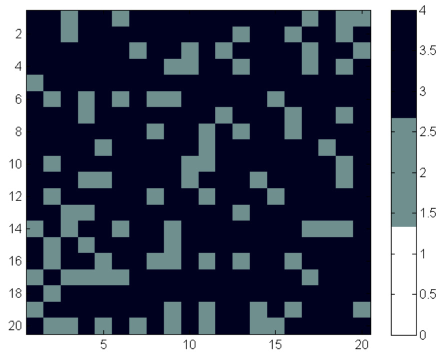
	NRK	TV2/RiksTV
Mux	1	2, 3, 4 ,5
% of population	98	15



(a) NRK users represented by black points



(b) NRK users represented by green points, Protection degree N= 3, 6.75 percent



(c) NRK users, Protection degree N= 5, 0 percent

Figure 7.3: Unused locations for Knowledge level 2: Actual channel usage of NRK MUX'es

Table 7.5: Unused locations for knowledge level 2, MUX 1

Protection degree N= 3	Protection degree N= 5
6.75 %	0 %

Table 7.6: Unused locations for knowledge level 2, MUX 2,3,4 and 5

Protection degree N= 3	Protection degree N= 5
74.25 %	45 %

For MUX 1 the first time- period: 06:00- 09:00, 29 % of the original NRK users are chosen randomly. Those users are referred to as active NRK users.

Then for the second time- period 20:00- 23:00, 41.9 % are chosen randomly from the original NRK user topology.

Result:

For a protection degree of N= 3, 57.75 % of the unused locations are location were the CRdevice can use the Grey Space. When the protection increases to N=5 , the percentage deceases to 27.75 %, seen in table 7.7. The locations are seen in figure 7.4.

For time- period 2 the location percentage deceased from 43 % to 13.25 % when increasing the protection degree from N= 3 and N= 5, table 7.8

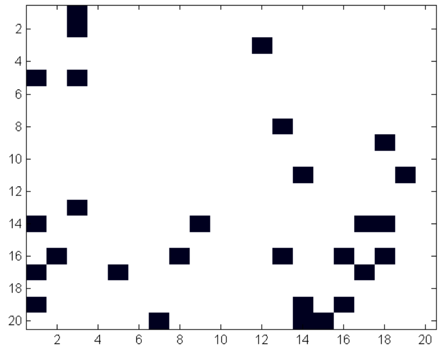
7.3.4 Result

As seen from the simulation the amount of unused channels increases as the knowledge of TV receiver increases.

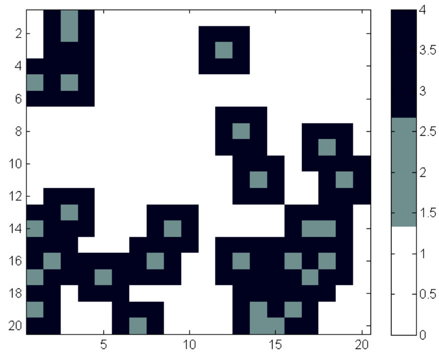
The result is not further evaluated because the result of the test case is not the focus. Our interest is taking to account a real topology. But an evaluation of the method and variables chosen is reviewed in the next section.

Table 7.7: Percentage of unused location for knowledge level 3, for time 1 and MUX 1

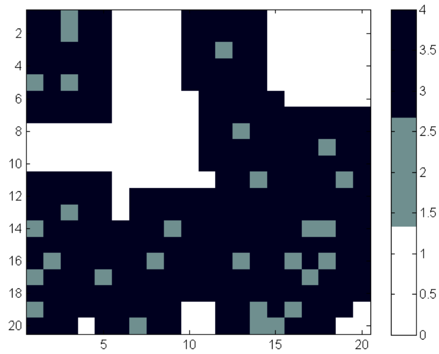
Protection degree N= 3	Protection degree N= 5
57.75 %	27.75%



(a) Time- period 1, locations of MUX 1 users



(b) Time- period 1: Protection degree N= 3, 57.75 percent



(c) Time- period 1: Protection degree N= 3, 27.75 percent

Figure 7.4: Knowledge level 3:Channel usage based on time: 06:00- 09:00, for MUX 1

Table 7.8: Percentage of unused location for knowledge level 3, for time 2 and MUX 1

Protection degree N= 3	Protection degree N= 5
43 %	13.25%

7.4 Evaluation

7.4.1 Topology

There are some choices regarding the topology that are simplified to be able to do an analysis of the subject. First of all the coverage area and transmitter information are not taken to account in the test case. An assumed of the area size is made, which is represented by a 20*20 matrix.

In the next chapter further evaluation of the choices done on the topology is reviewed.

7.4.2 TV receiver locations

The random density is chosen for the test case. Both when placing the 100 receivers and when choosing TV receives for the different knowledge levels. There may be other density structures that would fit reality better.

The random structure chosen for the test simulation can represent a typical rural area, where the population is scattered within a big area. But there may be other density structures, for instance one could chose a cluster like density that can illustrate that people usually live closer to each other. For instance in suburban areas households are located in clusters surrounding small towns etc. But for the test case the random density is regarded sufficient. In the next chapter household locations are uploaded from public records.

Choosing random user locations for each knowledge level

A more interesting discussion is the choice of random user locations for the knowledge levels.

When choosing users for RiksTV and NRK channel usage and when choosing users for a specific MUX, they are chosen randomly from the total topology. For instance for NRK users, 98 locations were chosen randomly from the total TV receiver locations, and were set as NRK user locations. The same method was used for RiksTV users. If more information was taken to account a more detailed analysis of the area could be made. For instance the users of a broadcaster may be located close to each other in a specific area, rather then scattered around.

The result of exploiting this, for instance by using a cluster like density would be that the amount of locations with Grey Space could increase. When taking to account a protection: the more scattered the TV receivers are located, the more areas they occupy. Resulting in less usable locations for a CR device. Thus, the random density is regarded the worst case scenario.

This choice is also made in the next chapter for the real case, and is done in lack of real information on the density. In practice the user location density of a certain broadcaster will vary depending on each area evaluated.

8 Simulation based on real values

8.1 Introduction

In this chapter three areas in Norway are chosen, and the percentage of unused locations and amount of unused frequencies are analyzed.

In chapter 7 the method used for the simulation is described and in addition a test case was presented. Section 7.1 and 7.3 is considered a common section used for both chapter 7 and 8.

The areas chosen are Vinje, Tynset and Lillehammer. The land area ranges from 478,2 km^2 - 3,106 km^2 and the population density ranges from 1/ km^2 - 54 /km^2 . In addition the population location pattern is different for each area. Vinje is the area that has the most complex population density, the households are scattered more then the other areas. In Lillehammer the density is focused in the middle of the topology and Tynset has two large areas were most of the population are found. The population density is seen in figure 8.1 for Vinje, 8.6 for Lillehammer and 8.5 for Tynset. Choosing these areas is regarded as a good measure to be able to analysis how the result changes for different types of areas in Norway.

First the simulation is done in Vinje and the unused locations and the amount of unused frequencies, both White Space and Gray Space, is presented. In section 8.3.7 the result is processed such that the result for each knowledge level can be compared.

In 8.3.8 - 8.3.9 the comparison of the three knowledge levels are conducted and evaluated. The last chapter presents the simulatatoin for Lillehammer and Tynset, which is compared to the result of Vinje.

8.2 Defining basic inputs

For each area the topology is described then the population density, and TV transmitter information is used to define a matrix such that the code can be run for each knowledge level.

8.2.1 TV transmitter information

An area may contain households receiving TV signals from different TV stations. Using the coverage planning map by Norges Television [29], the strongest TV transmitter at each area is found.

For instance in Vinje, the strongest transmitter in the area is Rauland which uses channels 25, 27, 32, 35 and 42. Using information from Norwegian Post and Telecommunications Authority (NPT) [41] there are in addition 12 TV transmitters that are connected to Rauland in a single frequency network (SFN). Which is a broadcast network were all transmitters uses the same channels to simultaneously provide TV service over a large area. The TV transmitter information in Vinje is found in table 8.3.

In the simulation all households in Vinje are assumed receives TV service from either the strongest TV transmitter or from other transmitter in the same SFN.

- There may be exceptions, for instance TV receivers at the edge of the area may receive signals from other TV transmitter that are not in the same SFN. In this thesis the information from NTV are assumed sufficient, thus these exceptions are neglectable.

- Another aspect on the choice of TV transmitter information is that there may be areas where the TV transmitters have overlapping TV service. For the TV transmitter in the same SFN, this has no effect on the result. But for TV transmitters using different frequencies it will affect the amount of White Space and Gray Space found in this thesis. In this thesis only the transmitters in the same SFN are evaluated.

8.2.2 Topology and TV receiver locations

The information on population density is retrieved from Statistics Norway (SSB) [27] and is found with different grid size: 100 m, 250 m and 1 km. The file retrieved for this thesis is based on the 1 kmx1 km grid size. For each household- location the information gives use the amount of households within a 1 km^2 area.

Method:

This information is used to define the MxN matrix and element size, described in chapter 7.

In table 8.1 a portion of the data for Tynset is shown. The first column shows the Id-number of the locations, then information on the amount of household in that position is given, and the third column gives the area the data belongs to: where 0501 is referring to Tynset.

Table 8.1: Information from SSB

ru1000m	bosatt	kommnr
2380006780000	7	0501
2420006786000	10	0501
2430006786000	26	0501

The information from SSB is mapped to the matrix by converting the data from the table.

For instance using the number from column one the ID number for the latitude and longitude are retrieved: 23.8, 67.8. The ID number are converted into x and y values. The size of the MxN matrix is defined as the difference between the largest and lowest ID value corresponding to latitude, and N is defined likewise by the Id number of the longitude values.

According to the second column there are 7 households in the 1 km^2 area. The corresponding (x,y) element in the matrix is marked as possible TV receiver location.

Discussion:

There are some issues to recognize:

The method used to convert the ID numbers, results in an overestimation of the area. As described the area are converted to a quadratic MxN matrix in the simulation. But the original information may have different shape.

For instance, in 8.3.1 it is mentioned that Vinje consist of 3106 km^2. In this thesis Vinje is represented with a 60 x64 matrix, which corresponds to an area of 3840 km^2. Thus, the method has expand the area with 734 km^2, when the grid-sizes are given in 1 km^2 this correspond to 734 matrix elemends.

This means there are 734 matrix elements which are not in the municipal of Vinje. The overestimation is seen for each area in table 8.2. This is a result of data, the data on population density tells us the location of households in Vinje, but it does not tell use explicitly where the Vinje border is drawn. The result is that there are locations, especially at the edge of the 60x64 matrix, considered as part of Vinje but that may be located in nearby municipals.

- There may be households in those areas belonging to another municipal, the worst case is if they use the same set of channel and therefore also need protection. Since the information retrieved is only for household in Vinje, there is no way of recognizing those households.

Table 8.2: The overestimation done using a MxN matrix

	Vinje	Lillehammer	Tynset
Represented MxN area	60 x 64	24 x 27	71 x 43
Assumed size	3840 km^2	648 km^2	3053 km^2
- real land area	3106 km^2	478 km^2	1880 km^2
= overestimation	734 km^2	170 km^2	1173 km^2
With 1 km^2 gridsize it corresponds to:	*734 grids*	*170 grids*	*1173 grids*

- In addition the result found when analyzing the expanded matrix, will overestimate the unused locations in Vinje. Because of the expansion it will take to account location outside Vinje.

The expansion is solved by marking the matrix elements at the corner of the quadratic area as “not apart of the topology”. This is sufficient because these are the areas that are assumed located in other municipals. For instance in Vinje 734 grids at the corners of the matrix are marked as “not apart of Vinje“.

For this thesis only households in the area evaluated are considered. Those households are not affected by the method, they are still protected from interference.

The areas marked can be seen in the figures .1, .3 and .2, found in the appendix. When calculating the unused locations the marked matrix elements are not taken to account, as they are considered outside the area evaluated.

8.2.3 Running code

The process explained and tested in chapter 7 is executed her for each area. After the information is converted in matrix format the code is run for all knowledge levels.

8.3 Vinje

8.3.1 Area description:

Is a municipality of Telemark county. The land area is 3,106 km^2 with a population of approximately 3,756 people and a population density of $1/km^2$. The population pattern is found along roads, with major part at the lower right side of the Topology as seen in figure 8.1.

TV transmitter:

Table 8.3: TV transmitter information at Vinje [29]

TV transmitter name	Rauland
Channel usage	25, 27, 32, 35, 42
SNF	12 transmitters using the same frequencies

The TV transmitter providing TV service in Vinje is RAULAND / BATNEHOV using channel 25, 27, 35, 32 and 42, it is a part of a SFN with 12 other transmitters, table 8.3.

8.3.2 Topology and receivers

The population density information is converted and the area is represented in a 60x 64 matrix. The matrix with the population density is shown in figure 8.1.

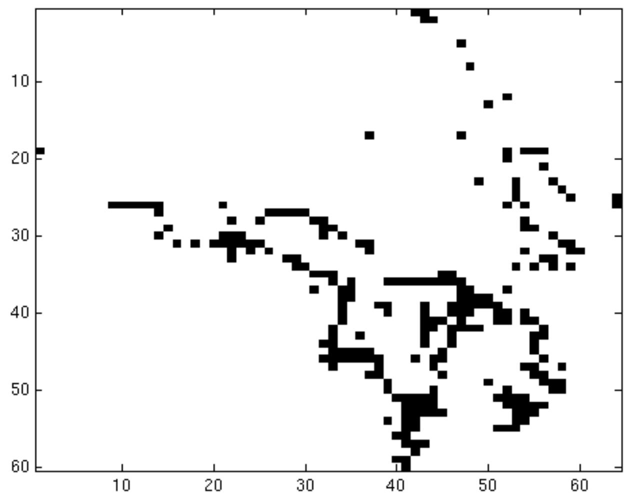


Figure 8.1: Population density at Vinje municipality

The percentage of unused locations within the 60x 64 area for each knowledge level and protection degree is found in the upcoming section.

8.3.3 Result setup

For each knowledge level there are two main points reviewed for both devices:

- The amount of locations within the area where the co-channel and adjacent channels are unused
- The amount of Gray Space and White Space available at those locations

Further, analyses on the household amount that may use these available channels are found.

In chapter 3.5 it was mentioned that the regulators in UK and USA has put restrictions on the channel usage within a service area. The co-channel and adjacent channels can not be used by a fixed device within the service area. Likewise for portable devices except when the transmitted power is lowered to 40 mW and 2.5 mW.

For the simulation, the locations where a 4 W fixed device and a 100 mW portable cognitive device can operate without causing interference are retrieved.

According to the restriction both the co-channel and adjacent channel can not be utilized within the service area for these devices. But in this thesis the restrictions are challenged. The result gives us information on the amount of locations where the restricted channel can be utilized by the CR device without causing interference to the TV receiver.

The location that can utilize the co-channels are found using N= 17 for the 4Watt device and N= 3 for the portable device. And using N= 3 for both devices, location where the adjacent channel may be reused are found. This was calculated in table 7.1.

In section 8.3.7 the result is summarized and in section 8.3. 8 the result for each knowledge level is compared.

Possible White Space amount in Vinje

For the specific case of Vinje, figure 8.2 illustrated the channel usage and using this information table 8.4 is calculated, which shows the channel occupency in Vinje.

As seen the adjacent and co-channels corresponds to 14 x 8 = 112 MHz spectrum.

- The co-channels in the area occupy 5* 8 MHz= 40 MHz of the spectrum
- The adjacent channels in Vinje occupy 72 MHz.

According to the restrictions those frequencies can not be used by any other device then the TV receiver. In this thesis the usage of these frequencies are analyzed and at locations and time were they are not used they are referred to as *Gray Space*.

In addition there is 208 MHz frequency that is not used by the TV transmitter in Vinje. This is the possible *White Space* amount. Before making a final decision on the actual White Space, an evaluation considering other TV transmitters and TV receivers at nearby areas using those channels must be done. This was discussed in section 8.2.1.

Table 8.4: Channel usage at Vinje considering the strongest TV transmitter

	Parameter	**Note**
Total amount of frequencies(F) for DTT	320 MHz	470- 790 MHz
Max # of F used at a location: Theoretically availible channels:	5x8 MHz= 40 MHz 280MHz	5 MUX/ 8 MHz
Adjacent and co-ch. frequency at Vinje: Theoretically availible channels:	5x8 MHz + 9x8 MHz= 112 MHz 208MHz	

The issue mentioned was that two TV service areas may be overlapping, both using different frequencies to deliver TV service. Resulting in TV receivers close to or within the area using a different set of channel. The protection they need must then also be calculated, which may lead to that the frequencies are not available in Vinje. Thus, the total 208 MHz White Space may not be usable, because some of the frequencies are protected.

In this thesis the transmitters found through NTV are used. In Vinje; Rauland and other TV transmitters in the same SFN are the only transmitters considered. Thus, the 208 MHz is considered the maximum possible White Space amount found in Vinje. Further analysis is not done on this subject

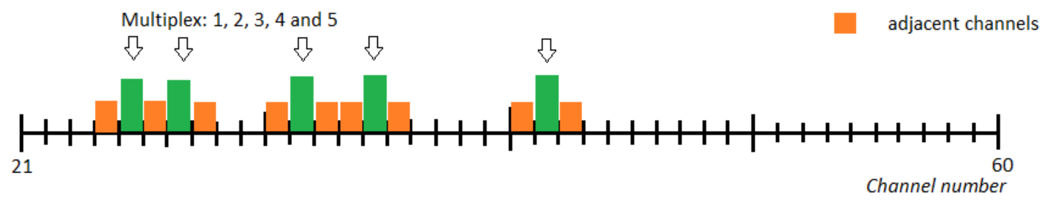


Figure 8.2: Channel usage of the strongest TV transmitter in Vinje: ch. 25, 27, 32,35,42

8.3.4 KN1: Possible channel usage

For possible channel usage all 5 MUX are assumed occupied, thus:

- The co-channels occupy 40 MHz
- Adjacent channels occupy 72 MHz. But to be able to compare the frequency value for all knowledge level the value is set to 80 MHZ.

Because the adjacent channel are set as occupying 80 MHZ, the White Space amount is $208 - 8MHZ = 200MHZ$.

Thus for Knowledge level 1, in addition to the 200 MHZ White Space at each location:

- Using 4 Watt CR device, 2.77 % of the locations may reused the co-channel. Thus, 40 MHZ is available
- Using 100mW CR device, 69.89 % of the locations may reused the co-channel. Thus, 40 MHZ is available
- Using both device, 69.89% of the locations contain 80 MHz Gray Space

	N= 3	N= 7	N= 17
Number of none protected locations	2170.00	1181.00	86.00
Percentage of the total area with Gray Space	69.89	38.04	2.77

The color map showing the locations with unused frequencies is shown in figure 8.3. The left figure shows the unused locations represented as white matrix elements, for N=3. This corresponds to a protection of 62m, 281m and 910 m. The figure to the right shows the unused location for a protection of 7.35 km. The location marked with an X is the location considered outside Vinje municipal.

In chapter 7 the min. distance required between the CR device and the TV receivers was defined as:

- 910 m: for a portable 100mW device using co-channel

- 62 m: for a portable 100 mW device using adjacent channel

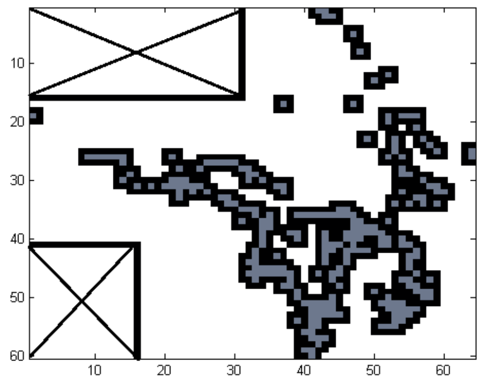
- 7.35 m: for a fixed device using co-channel

- 281 m: for a fixed device using adjacent channel

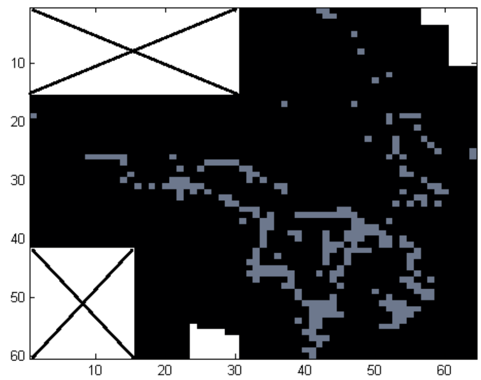
It was discussed that because of the grid size of 1 km x 1km, the protection degree N= 3 were used for the distance 62 m, 281 m and 910 m. And N= 17 for the min-distance of 7. 35 m.

The result show that even when all 5 MUX'es are assumed received by all households within the service area, there are large areas were the MUX's can be utilized by a CR device.

For knowledge level 1,the unused location do not contain any households. Since all households within the area is assumed as receiving all 5 MUX. For the next sections a better knowledge on the TV receivers and their channel usage makes it possible for household to utilize the available frequencies.



(a) Protection corresponding to 62m and 281 m, 77.76 percent



(b) Protection corresponding to 7,35 km, 26.64 percent

Figure 8.3: KN1: Unused locations for protection degree N= 3 and N= 17

On the other hand the information on TV receivers are based on SSB data, and it was mentioned that the data does not include other buildings and condo areas. Thus although there are no households there may be other types of buildings that can used the unused frequencies.

8.3.5 KN2:Actual channel usage

For actual channel usage, the subscriberes for the difference broadcasters are split. This is reviewed in section 5.3.3.

- The co-channels for MUX 1 occupy 8 MHz
- Adjacent channels for MUX 1 occupy 16 MHz.
- The co-channels for MUX 2, 3, 4 and 5 occupy $4MHZ * 8MHZ = 32MHZ$.
- Adjacent channels for MUX 2, 3, 4, 5 occupy $4MHz * 2(adjacentchannels) * 8MHz = 64MHz$.

The resulting unused location percentage is presented for the NRK- MUX and for RiksTV-MUX'es. Thus for Knowledge level 2, in addition to the 200 MHZ White Space at each location:

MUX 1	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	2424.00	1614.00	475.00
Percentage of the total area containig Gray Space	78.07	51.98	15.30

MUX 1 - NRK

- Using 4 Watt CR device, 15.30 % of the locations contain 8 MHz Gray Space, for co-channel usage
- Using 100mW CR device, 78.07 % of the locations contain 8 MHz Gray Space, for co-channel usage
- Using both device, 78.07% of the locations may contain 16 MHz Gray Space, for adjacent channel usage

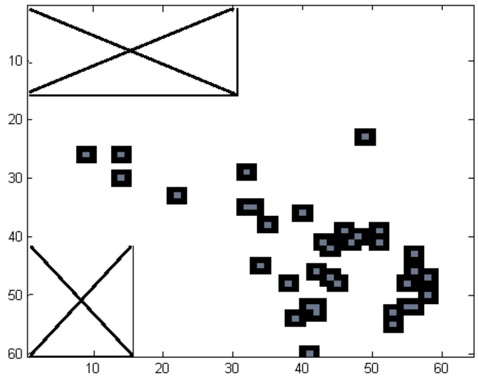
MUX 3, 4 and 5(and 2)- RiksTV

MUX 2, 3, 4 and 5	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	2839.00	2227.00	1033.00
Percentage of the total area containing Gray Space	91.43	71.72	33.27

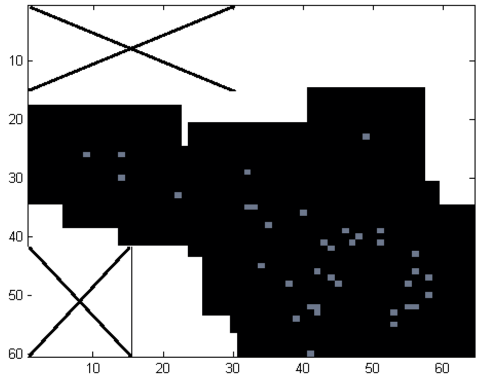
- Using 4 Watt CR device, 33.27 % of the locations contain 32 MHz Gray Space, for co-channel usage
- Using 100mW CR device, 91.43 % of the locations contain 32 MHz Gray Space, for co-channel usage
- Using both device, 91.43 % of the locations contain 64 MHz Gray Space, for adjacent channel usage.

The results assume that one has knowledge on which broadcaster a given TV receiver is using. The amount of unused locations when evaluating one MUX increases, the result can be seen clearer for the TV receiver using RiksTV because they have fewer users. Instead of assuming that all households are using all 5 MUX'es, the information tells use that RiksTV MUX'es only are used by 15 % of the households, which leads to a better mapping of the channel usage and the locations with available channels. Figure shows the result of unused locations when considering RiksTV subscribers.

To be able to compare the knowledge levels further processing must be done on the result. In section the result for all the MUX'es are combined such that the result for knowledge level 3 can be retrieved.



(a) Protection corresponding to 62m and 281 m, 77.76 percent



(b) Protection corresponding to 7,35 km, 26.64 percent

Figure 8.4: KN2: Unused locations containing Gray Space,for protection degree N= 3 and N= 17

8.3.6 KN3: Time based channel usage

The amount of unused location for two time- period are retrieved in this section. The MUX evaluated are MUX 1, MUX 3(and 2) and MUX 4(and 5). This was discussed in section 5.3.4, and the amount of TV receivers using each MUX is calcuated and seen in table 5.3. The numbers for MUX 3(/2) and MUX4(/5) are combined to represent the total unused location for RiksTV MUX in time.

The co-channel and adjacent channel occupancy for these MUX are summarized: For MUX1/ NRK usage

- Co-channel occupy 8 MHz
- Adjacent channels occupy 16 MHz

For MUX 3(/2) and MUX 4(/5)- Rikstv usage

- Co-channel occuped $4MHZ * 8MHZ = 32MHZ$.
- Adjacent channel occuped $4MHz * 2(adjacentchannels) * 8MHz = 64MHz$.

Time- period 1:

Time 1, NRK MUX	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	2663.00	1851.00	606.00
Percentage of the total area	85.76	59.61	19.52

- Using 4 Watt CR device, 19.52% of the locations contain 8 MHz Gray Space
- Using 100mW CR device, 85.76 % of the locations contain 8 MHz Gray Space
- Using both device, 85.76 % of the locations contain 16 MHz Gray Space

Time 1, Rikstv MUX	N= 3	N= 7	N= 17
Number of none protected locations	3096.00	3056.00	2816.00
Percentage of the total area	99.71	98.42	90.69

- Using 4 Watt CR device, 90.69% of the locations contain 32 MHz Gray Space, for co-channel usage
- Using 100mW CR device, 99.71% of the locations contain 32 MHz Gray Space, for co-channel usage
- Using both device, 99.71 % of the locations contain 64 MHz Gray Space, for adjacent channel usage

Time- period 2:

Time 2, NRK MUX	N= 3	N= 7	N= 17
Number of none protected locations	2537.00	1701.00	475.00
Percentage of the total area	81.71	54.78	15.30

- Using 4 Watt CR device, 15.30% of the locations contain 8 MHz Gray Space, for co-channel usage
- Using 100mW CR device, 81.71 % of the locations contain 8 MHz Gray Space, for co-channel usage
- Using both device, 81.71 % of the locations contain 16 MHz Gray Space, for adjacent channel usage

Time 2, Rikstv MUX	N= 3	N= 7	N= 17
Number of none protected locations	3054.00	2895.00	2345.00
Percentage of the total area	98.36	93.24	75.52

- Using 4 Watt CR device, 75.52 % of the locations contain 32 MHz Gray Space, for co-channel usage
- Using 100mW CR device, 98.36 % of the locations contain 32 MHz Gray Space, for co-channel usage
- Using both device, 98.36 % of the locations contain 64 MHz Gray Space, for adjacent channel usage

The result show that for the average marked share of each MUX there is a significant amount of unused locations per time. This amount changes dynamically as the TV channel is changed between the MUX's, the TV channel are found in table 5.1. For instance, when a household changes the TV channel from Visasat 4 (MUX3) and TV 3 (MUX3) there is no change in the amount of Gray Space available. But if it's changed from NRK1 (MUX1) to TVNorge (MUX3), the Gray Space amount will change because the MUX used is changed. For a CR device to utilize this it must track this change and be able to protect the right MUX from interference. The technology today is not capable of delivering this protection.

To give a better understanding of the result, the results for each knowledge level are combined.

8.3.7 Discussion of the result

To be able to compare the knowledge levels further processing must be done on the result. There are mainly two steps done in this section:

1) The total amount of frequencies available at every location is summarized. This is found using the m-file *findSum*, it adds the locations containing co-channel and adjacent channels.

The m-file gives separate result for the 4 Watt fixed device and the portable 100 mW device. For the fixed device using N= 17 which indicates were the co-channel is available and N= 3 were the adjacent channel is available. For the portable device, N=3 is used to indicate were both the co-channel and adjacent channel are available. By summarizing the frequency at each area the amount of unused locations containing a specific frequency amount is retrieved.

In addition the m-file counts the amount of household locations that can utilize the frequencies. For a given channel- usage the unused locations are compared with the original topology. The amount of unused locations is used to define the amount of household locations. At these locations the households will be able to use these frequencies.

2) To be able to give a wholesome picture of the result, the result is evaluated further and summarized in section 8.3.8.

Table 8.5: Knowledge level 1:The amount of Gray Space for a **4 watt Fixed device**

Frequency amount	Amount of location	distinctly found at % of locations	total percentage of location	household locations
80 MHz	2084	67.1 %	69.9 %	0
120 MHz	86	2.8 %	2.8%	0

The tables below shows two tables for each knowledge level. One for the 4 W fixed device and one for the 100mW portable device.

For instance for knowledge level 1, table 8.5 show that if a 4 W fixed CR device is considered: 67.1 % of the locations contain 80 MHz and 2.8 % contain 120 MHz. But there are no households at those locations. The sum is 69.9 %, thus the TV receivers and the protection area for the fixed device occupy 69.9% of the locations.

Considering a portable device 69.9 % of the locations having 120 MHz, but there are no households found at these locations either.

- The amount of household locations is not the focus of this thesis but it will have an affect when considering the value of the Gray Space found. If there is Gray Space but no device at those locations that can utilize it, the economical gains may decrease.

  For knowledge level 2 and 3 the unused location will contain households that can utilize the Gray Space. For knowledge level 2 a maximum or 138 household locations will be able to uses the Gray Space, both for fixed and portable devices. For knowledge level 3 this increases to 243 household locations. The actual amount of households that can use the Gray Space will depend on each 1 km* 1km household location. For instance in table 8.1 the amount of household at each location ranges from 7- 26 households.

For knowledge level 2 and 3 it is seen that the amount of Gray Space varies, espessialy for the fixed device. Where the amount ranges from 16 MHz to the maximum of 120 MHz for all knowledge levels.

The values are not further discussed rather they are used in the next section to give a clearer understanding of the result focusing on the total unused location and Gray Space.

Table 8.6: Knowledge level 1:The amount of Gray Space for a **100mW portable device**

Frequency amount	Amount of location	Percentage of location	household locations
120 MHz	2170	69.9 %	0

Table 8.7: Knowledge level 2:The amount of Gray space for a **4 W fixed device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
16 MHz	31	1 %	92.4 %	138
64 MHz	387	12.5 %	91.4 %	133
80 MHz	1407	45.3 %	79 %	27
88 MHz	12	0.4 %	33.7 %	14
96 MHz	59	0.19 %	33.3 %	14
112 MHz	5110	16.5 %	31.4 %	3
120 MHz	4630	14.9 %	14.9 %	1

Table 8.8: Knowledge level 2:The amount of Gray space for a **100mW portable device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
24 MHz	31	1 %	92.4 %	138
96 MHz	446	14.4 %	91.4 %	133
120 MHz	2393	77.1 %	77.1 %	16

Table 8.9: Knowledge level 3.1:The amount of Gray space for a **4 W fixed device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
16 MHz	21	0.7 %	99.7 %	243
80 MHz	259	8.3 %	99 %	237
96 MHz	412	13.3 %	90.7 %	232
112 MHz	1798	57.9 %	77.7 %	64
120 MHz	6060	19.5 %	19.5%	1

Table 8.10: Knowledge level 3.1:The amount of Gray space for a **100mW portable device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
96 MHz	433	13.9 %	99.7 %	243
120 MHz	2663	85.8 %	85.8 %	69

Table 8.11: Knowledge level 3.2:The amount of Gray space for a **4 W fixed device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
16 MHz	14	0.5 %	98.8 %	234
64 MHz	109	3.5 %	98.4 %	229
80 MHz	598	19.3 %	94.8 %	196
88 MHz	2	0.1 %	75.6 %	189
96 MHz	422	13.6 %	75.5 %	189
112 MHz	1450	46.7 %	61,9 %	38
120 MHz	473	15.2 %	15.2 %	1

Table 8.12: Knowledge level 3.2:The amount of Gray space for a **100mW portable device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
24 MHz	14	0.5 %	98.8 %	234
96 MHz	531	17.1 %	98.4 %	229
120 MHz	2523	81.3 %	81.3 %	45

Table 8.13: Result: White Space and Gray Space amount in Vinje: Considering a Fixed device

%	White space amount	KN1	KN2	KN3 time 1	KN3 time 2
20 %	200 MHz	80 MHz	120 MHz	112 MHz	112 MHz
40 %	200 MHz	80 MHz	88 MHz	112 MHz	112 MHz
70 %	200 MHz	-	80 MHz	112 MHz	96 MHz
90 %	200 MHz	-	64 MHz	96 MHz	80 MHz

Table 8.14: Result: White Space and Gray space amount in Vinje: Considering a portable device

%	White space amount	KN1	KN2	KN3 time 1	KN3 time 2
20 %	200 MHz	120 MHz	120 MHz	120 MHz	120 MHz
40 %	200 MHz	120 MHz	120 MHz	120 MHz	120 MHz
70 %	200 MHz	-	120 MHz	120 MHz	120 MHz
90 %	200 MHz	-	96 MHz	96 MHz	96 MHz

8.3.8 Discussion summary

In the introduction it was stated that we will find the amount of unused locations and unused frequencies when changing the knowledge levels. For the sake of comparison, the result from last section is summarized to give the results for specific percentage. The percentage ranges from 20 % - 90 %.

For instance for knowledge level 1 in table 8.5 it was seen that, 67.1 % of the locations contain 80 MHz and 2.8 % contain 120 MHz. In the table 8.13 those values are fitted for the percentage in the table. Thus, 40 % and less locations contain 80 MHz, Since this is the lowest percentage in the table, locations containing 120 MHz are not included.

The result on the amount of White Space and Gray Space for 20 %, 40 %, 70 %, and 90 % of the location are presented in table 8.13 for a fixed device and in table 8.14 for the portable device.

For the result on the amount of unused frequencies to be clearer the result is compared with how the situation is in Norway today(A), what the unused frequency amount is using the TX database (B) and then how it increases when using the RX database(C).

A) As the band is today no other than the licensed user of the TV band are using the TV band spectrum. Thus the total sum of 430 MHZ are utilized at zero % of the locations in

Vinje. Both the White Space and Gray Space is not taken to account.

B) Using the TX database and considering channels from one TV transmitter and other transmitters in the same SFN, there is an amount of 200 MHz White Space at 100 % of the area evaluated.

C) Using information on TV receiver location and the protected area, additional unused frequencies are found called Gray Space.

Fixed device

Focusing on the Gray space amount considering a 4 Watt fixed device:

- KN1. Using Knowledge level one all households are considered protected from interference although they do no use or own a TV. For this method, there is a maximum of 80 MHz in 40 % of the locations. The amount for 90 % of the locations is not defined.
- KN2. For knowledge level 2 information on which broadcaster a household is subscribing to is used. The maximum Gray Space amount increases to 120 MHz, for 20 % of the locations. Using this method a minimum of 64 MHz is found at 90 % of the locations. For the KN1, the Gray space amount for 90 % of the location was not defined. The minimum increase of Gray Space gained by using KN2 is 8 MHz, and it is found at 40 % of the locations. A maximum increase of 40 MHz is found at 20 % of the locations.
- KN3. When using information on what time the TV is used, a greater amount of Gray Space is retrieved.

  - Except for the maximum Gray Space found of 112 MHz. This is a result of how the households are located. If the households in KN3 are more scattered than those considered in KN2, the protected area will cover a larger area. Thus, less amount of Gray space is found.

  For 90 % of the location considering time -period between 06:00- 09:00, the Gray Space consists of 96 MHz. When considering a time- period where the TV activity is lower the Gray Space is 80 MHz. Thus regardless of the TV activity in time, the Gray Space found is greater when the time usage is considered.

  Considering the time were most TV activity is found, a minimum increase of 8 MHz is found by changing from Knowledge level 2 to Knowledge level 3 time2, at 20 % of the locations. And a maximum increase of 16 MHz at 90 % of the locations between the same levels.

Portable device

When a portable CR device is considered the amount of Gray Space is almost static.

- For knowledge level 1, 90 % and 70 % of the location are not defined, but a maximum of 120 MHz is found at 40 % of the location. And this level is the same for all knowledge level.
- A minimum of 96 MHz is found at 90 % of the location when considering Kn2 and kn3, and a maximum of 120 MHz: Which mean that all the frequencies planned to be used for the TV service are unused at 90 % of the location, and can be utilized by at 100 mW device.

The result found for the amount of Gray Space is consistent with what was claimed in the introduction. The TV broadcasting band is underutilized and by using the TX database the area is overprotected and the unused frequency amount is underestimated by only taking to account the White Space. By registering TV receivers additional amount of unused frequencies are considered.

The increase of Gray Space amount ranges from 64- 96 MHz at 90 % of the locations when considering a 4 W device. And for a 100mW device it increase to 96 MHZ at 90 %, and at 70 % of the locations the total TV broadcasting band of 320 MHz can be utilized without disturbing the TV reception.

8.3.9 Evaluation of Result

The result found in this thesis has value both for the license holder of the spectrum and for the application provider.

For instance, the license holder may be interested to know how ineffective the usage is at certain locations and that large portions of the band may be utilized for other purposes without disturbing the primary users. There is an economical gain that can be achieved if the broadcasters decide to lease out the spectrum for other applications, for the case of Norway the usage of the band for other application is in accordance with the Geneva agreement of 2006. But the spectrum usage may be used by the broadcaster itself as a backup spectrum or used for hybrid technology.

For an application provider the amount of households that may utilize these unused frequencies has more value. For instance for knowledge level 2 there is a maximum of 138 household locations that can utilize the Gray Space, seen in table 8.7 and 8.8. Thus, at those locations the household can be provided in- house applications using the Gray Space.

The variation of Gray Space amount vs. CR device

This section discusses mainly how the amount of Gray Space changes for the knowledge levels, and based on that it is given recommendations on how the Gray Space should be used.

It is stated in the previous section that the RX database will make the Gray Space available for the Cognitive radio device.

- For instance for a portable device the Gray Space consist of 96 MHz, and is found at 90 %, of the locations. At those locations using table 8.6, 8.8, 8.10 and 8.12: the household location ranges from 0 for knowledge level 1, to 133 for KN2, and 243 and 224 household locations for KN3 time 1 and 2, respectively.

Although there is a great amount of Gray Space at these locations, the amount can change because it depends on the TV receiver.

The TV receivers are the primary users of the TV broadcasting band and must be given protection regardless of where and when they are active. For instance, if a CR device is operating using one of the channels ranging from 21- 60[section 5.2], and if a TV receiver starts using the same channel, then it is no longer unused and can not be utilized by the CR device. The importance of this aspect varies depending on the knowledge levels.

KN1. For KN1 all households are protected, thus this is not a problem. In section 8.3.4 it is explained that condos and other buildings are not taken to account.

KN2. For KN2, information on which broadcaster is delivering TV service at a household is registered. Thus, if a household changes its subscription the Gray Space amount changes.

For instance if a household receiving channels from NRK (MUX 1), changes it's subscription to RiksTV (MUX 3, 4 and 5, including TV2). Then the Gray space amount, considering only the co-channel, will change from $4 * 8MHz = 32MHz$ to 8 MHz. The worst case scenario is if the change in subsriptions result in no Gray Space at all. This can happen over a longer period of time.

KN3. For KN3, the change occurs if the TV channel is changed: between a TV channel transmitted through one MUX to a TV channel used in another MUX. This was discussed in 8.3.6. This change in the Gray Space amount can happen in a second, thus the Gray Space for KN3 may not be reliable to be used as the primary capacity source for a device or system.

The rate of change on the Gray Space amount is greatest for KN3.

Based on this discussion it is stated that the CR device should not relay entirely on the Gray Space for its operations, especially not a fixed device needing high capacity.

- For instance the 4 W fixed device is as mentioned in the introduction, used to represent an IEEE 802.22- WRAN Base station. The base station in the WRAN system is used to communicate between several devices (CPE). Thus, the change in the capacity when only considering Gray Space may not be reliable for the system if high capacity is needed over a longer period.

But it is a good resource to be used whenever one needs extra spectrum, increasing the system capacity. A fixed CR device needing high capacity over a larger time period should use the Gray Space in combination with other frequencies, like the White Space.

When considering a low power device as the 100 mW CR device, the Gray Space found is excellent to deliver peer to peer connectivity between devices. There are large amount of frequencies, up to 96 MHz at 90 % of the locations and in addition there are many households at those locations. Making it convenient to deliver in-home application as well.

- One aspect not focused on in this thesis is whether the locations where the Gray Space is found is usable. When one takes into account the interference that a high powered TV transmitter can have on the CR device, there will be an area surrounding the TV transmitter that may not be of use for the CR device. When a cognitive radio using the Gray Space is evaluated, this aspect should be taken into account. Thus, further work on this aspect is needed when considering to utilize the Gray Space.

Knowledge leves

To be able to use the Gray Space the knowledge levels must be implemented. In this section the knowledge levels are compared in relation to the rate of change in the Gray Space amount, the sensitivity/ privacy of the information needed and on how complicated the implementations are. Then a knowledge level is recommended based on the discussion.

- KN1. Knowledge level 1 is the level demanding least information from both the broadcaster and the TV owner. Here all households are guaranteed protection regardless whether they use the TV service or not. The advantage is that no sensitive information is needed in addition the amount of Gray Space is constant as discussed in the previous section. Which also mean that the RX database only needs minor updates, for instance when a household buys a Television. On the other hand, there are no households at the unused locations, for instance as seen in table 8.5. Which will limit the type of applications that can be implemented: In- home applications is regarded as one of the applications where the Gray Space is appropriate to be used as stated in the previous section. Using KN1 will limit in-home applications because there are noe household at those unused locations.
- KN2. Knowledge level 2 demands registration on which broadcaster a household is subscribed to. The advantages of knowledge level 2 is that the level of Gray

Space is high and stabile, only needing an update when a household changes its subscription or buys a Television. In addition the Gray Space is found at household locations, enabling in-home applications as well.

- KN3. Knowledge level 3 demand real time information on which channels, between ch. 21- 60, are used at a households. The advantage is that it results in the largest amount of Gray Space. On the other hand, this level is the most complicated of the knowledge levels demanding real time information and sensitive information on what TV channel is watched at a household. In addition, the database needs a continually update because the TV channel can change in a second, as discussed in the previous section. Such a change is not recommended to be registered in a database because delays in the update is not accepted, in this thesis an IP connection is assumed and a delay can occur if the IP connection is slow. But as mention the registration is not limited to be used through an IP connection, any other method used to update the channel usage must enable a real time update. Further research is needed on this subject.

Knowledge level 2 is considered the best choice because it results in a great amount of Gray Space and in addition there are households at those locations that can utilize the unused frequencies. The amount of Gray Space is stabile, which gives a better security compared to KN3. In addition there are significant amount of households at those unused locations, which makes it more desirable compared to KN3.

There are still some issued to recognize. KN2 demand information that is private both for the customer and the broadcasters. For instance information on which broadcaster a household is subscribing to and were the subscribers of certain broadcaster are located. The latter is business sensitive information, which can be used by for instance competitors. These are issues that need more research.

Regardless of the issues, the opportunity on the economical gain and the many application that can be supplied using this band makes this a method worth investigating.

8.4 Other areas

In these chapters the result for Tynset and Lillehammer are presented. The method is similar to Vinje thus to avoid repeating unnecessary text only the amount of unused frequencies for 20 % , 40 % , 70 % and 90 % of the locations are shown in this section. The rest are found in the appendix.

Table 8.15: TV transmitter information at Tynset

TV transmitter name	Tron
Channel usage	26, 34, 49, 23, 40
SNF	3 transmitters using the same frequencies

8.4.1 Tynset

Area description

Is a municipality in Hedmark County. The land area is about 1.880,2 km^2 with a population of 5,463 people and a population density of $3/km^2$ [27]. When looking at the population pattern, there are three distinct roads and the households are found located along these roads and other smaller roads.

Compared to Vinje it covers a smaller area but with a higher population density. Compared to Lillehammer it is larger, but has lower population density.

TV transmitter info:

The strongest transmitter is TRON with channels 26, 34, 49, 23, 40. There are 3 transmitters in the area using the same frequency. They are all connected in a SFN- single frequency network. The area is represented in a 71x43 matrix and is seen in figure 8.5.

The result is conducted using the same method as in Vinje. The result for the fixed device is found in 8.16, and the result for the portable device is found in table 8.17.

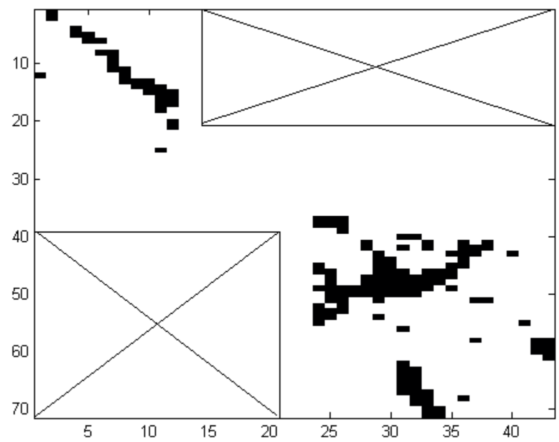


Figure 8.5: Population density at Tynset municipality

Table 8.16: Result: White Space and Gray Space amount in Tynset, considering a Fixed device

%	White space outside service area	KN1	KN2	KN3 time 1	KN3 time 2
20 %	200 MHz	80 MHz	112 MHz	120 MHz	120 MHz
40 %	200 MHz	80 MHz	80 MHz	112 MHz	112 MHz
70 %	200 MHz	80 MHz	80 MHz	112 MHz	96 MHz
90 %	200 MHz	-	64 MHz	80 MHz	80 MHz

Table 8.17: Result: White Space and Gray Space amount in Tynset, considering a portable device

%	White space outside service area	KN1	KN2	KN3 time 1	KN3 time 2
20 %	200 MHz	120 MHz	120 MHz	120 MHz	120 MHz
40 %	200 MHz	120 MHz	120 MHz	120 MHz	120 MHz
70 %	200 MHz	120 MHz	120 MHz	120 MHz	120 MHz
90 %	200 MHz	-	96 MHz	96 MHz	96 MHz

Result

Table 8.16 and 8.17 show the Gray and White Space amount in Tynset when considering the 4 W and 100 mW device, respectively. The method used in Vinje is implemented here and the detailed results of the amount of unused frequencies: both White and Gray Space, for each knowledge level are found in table .3 -.10 in the appendix.

The result is similar for Tynset as for Vinje, with small deviations. In average there is 94 MHz for the 4 W device and 115 MHz when considering the 100 mW device, compared to 96 MHz and 115 MHz in Vinje, respectively. Which is a average increase of 2 MHz for the fixed device. The values are compaired further in section 8.4.3.

8.4.2 Lillehammer

Area description:

Is a municipality of Oppland county. The land areal is about 478,2 km^2 and a population of approximately 26000 people. The population density is 54 km^2 The population pattern her is denser compared to the other two areas.

Table 8.18: TV transmitter information at Lillehammer

TV transmitter name	Lillehammer/Korpeberget
Channel usage	33, 43, 56, 27, 31
SNF	5 transmitters using the same frequencies

Lillehammer has a highest amount of population density 54 km^2 compared to $1/km^2$ in Vinje. But it has the smallest land area.

TV transmitter info:

The strongest transmitter is LILLEHAMMER / KORPEBERGET using the channels 33, 43, 56, 27 and 31. There are 5 transmitters in the area using the same frequency, 8.18. The area is represented in a 24x27 martrix, the population density within the 24x 27 matrix is seen in figure 8.6.

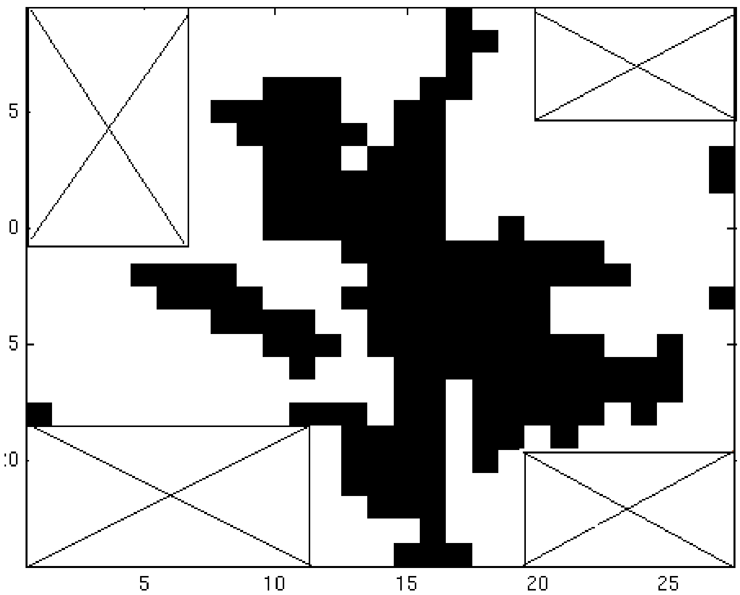


Figure 8.6: Population density at Lillehammer municipality

Result

Table 8.19 and table 8.20 show the amount of White Space and Gray Space in Lillhammer for 20% , 40% , 70 % and 90 % of the locations. The values are calculated using the

Table 8.19: Result: White Space and Gray Space amount in Lillehammer, considering a Fixed device

%	White space	KN1	KN2	KN3 time 1	KN3 time 2
20 %	200 MHz	80 MHz	80 MHz	120 MHz	96 MHz
40 %	200 MHz	-	80 MHz	96 MHz	80 MHz
70 %	200 MHz	-	64 MHz	80 MHz	64 MHz
90 %	200 MHz	-	-	64 MHz	64 MHz

Table 8.20: Result: White Space and Gray Space amount in Lillehammer, considering a portable device

%	White space	KN1	KN2	KN3 time 1	KN3 time 2
20 %	200 MHz	120 MHz	120 MHz	120 MHz	120 MHz
40 %	200 MHz	-	96 MHz	120 MHz	120 MHz
70 %	200 MHz	-	-	96 MHz	96 MHz
90 %	200 MHz	-	-	96 MHz	96 MHz

same method as in Vinje and extended tables containing unused frequencies for each knowledge level are found in table .11 - .18, found in the appendix.

The result is lower in Lillehammer than in Vinje. In average there are 81 MHz considering a 4 W device and 109 MHz for the 100 mW device, compared to 96 MHz and 115 MHz in Vinje, respectively. The values are compaired further in section 8.4.

8.4.3 Result Summary

In the previous chapter the White and Gray Space amount in Tynset and Lillehammer were calculated. As mentioned in section 8.1, the three areas chosen are different in land area, population density and household location pattern.

Vinje is the largest area evaluated and the population is scattered the most compared to the other areas. Tynset has a smaller land area than Vinje and the population is mainly located in two areas. Lillehammer consists of the smallest land area with greater amount of households located in one large cluster.

- For Vinje it was stated that for 90 % of the locations there is between 64- 96 MHz of Gray Space in Vinje, considering KN2 and KN3 for a 4 W device. The result in Tynset is the same. While for Lillehammer 64 MHz is found when knowledge on TV usage in time is taken into account (KN3).
- When considering a 100mW device in Vinje, the amount of Gray Space is 96 MHz

for KN2 and KN 3. For 70 % of the locations the whole TV band can be utilized. The same result is found in Tynset, the result is then for all knowledge levels and not only KN2 and KN3. In Lillehammer 96 MHz is found at 70 % of the locations, this result is when only considering knowledge on TV usage in time (KN3).

The larges difference on the result is seen in Lillehammer, where as mentioned the average Gray Space amount is 81 MHz and 109 MHz considering a 4 W and a 100m W, respectively. While for Vinje the average Gray Space amount is 96 MHz for the 4 W device and 115 for the 100 mW device. Thus, in Lillehammer there is an decrease of 15 MHz and 6 MHz of the Gray Space amount when considering a 4 W and a 100mW, respectively.

- This decrease of the Gray Space is mainly a result of the combination between population density and land area. There are approximately 26000 people living in Lillehammer municipal scattered within an area of 478,2 km^2, compared to 3756 people in Vinje within 3106 km^2. This causes larger part of the area to be protected.

When comparing Tynset and Vinje the unused location containing Gray Space amount is similar with small deviations, with an average decrease of 2 MHz for the fixed device in Tynset.

- Such a small deviation proves that the model suggested in this thesis represent the Gray Space amount in the TV broadcasting band in the appropriate way and thus can be used as guidelines for estimation of Gray Space amount for the secondary usage of the TV band. For areas were the population density is high compared to the land area, less Gray Space must be expected. In this thesis the average decrease in Lillehammer was found to be between 6- 15 MHz lower depending on the device.

9 Evaluation of method

In this chapter evaluation on how the grid size and C/I requirements affect the results is executed.

9.1 Grid size: Overestimates the protection

In chapter 6 the needed protection surrounding the TV receiver was calculated to be 7.35 km and 281 m for a CR device with 4 W transmit power, and 910 m and 62 m for a 100 mW CR device. For the simulation the population information was given per 1 km x 1 km grids size, which led to corresponding matrix elements of N= 3 and 17. The value of the N size was chosen by rounding up the protection distance. The overestimation was discussed in the method section of chapter 7.2.1.

In this section it is discussed how the overestimation differs when using 1 km, 250 m and 100 m grid sizes. It is then conlcuded that the 100m X100 m grid size is the one fitted to represent all the protection distances needed.

To avoid overestimating the protection needed at a TV receiver location, the grid size should result in an area corresponding to the min. protection needed defined by the min. distance. The minimum protection area needed is a circular area surrounding the TV receivers, defined as $\pi * r^2 km^2$ where r is the protection distance.

For instance evaluating the protection needed for a 4 W fixed Cognitive radio device, the eq. results in a min. needed protection area of $\pi * 7.35^2 km^2 = 169.7$.

The areas protected for the grid size of 100 m , 250 m and 1 km are shown in table 9.1, it is seen that:

- For the 1km x1km grid size the calculated protection degree N is 17, this corresponds to a land area of 289 km^2. Thus the overprotection made is 289 km^2 -169.7 km^2 = 119.3 km^2m.
- When the information is based on 250 mx250m grid size, we need $\frac{7.5km}{250m} = 30$ matrix elements. Using eq 7.1 the protected degree N is then 61, which corresponds

to a land area of 232.56 km^2. The overprotection decreases to 232.56 km^2 -169.7 km^2 = 62.86 km^2.

- For a grid size of 100m x100m the needed distance requires $\frac{7.35km}{100m} = 75$ matrix elements, the protection degree N= 151. A 151m x 151m grid area corresponds to 228 km^2, decreasing the overprotection to 228 km^2 -169.7 km^2 = 58.3 km^2.

As seen lower grid sizes results in less overprotection. The overestimation is significant especially for lower protection distances. For instance for a min. distance of 62 m the overprotection when using a 1 km x 1km grid is equal to $0.012 - .9km = 8.98km$. The areas protected for the grid size of 100 m , 250 m and 1 km are shown in table 9.1.

For fixed device the difference in ratio between the overestimated protection done by using 1 kmx1 km and the min. protection is $\frac{289}{169.7} = 1.7$. Thus, the overestimation increases the min. needed area with 70 %. While for the portable the ratio is $\frac{9}{2.6} = 3.46$, which means the overestimation increases with 246 % compared to the needed value. As seen using the 1 km grid size, will result in larger overestimation for low protection distances. In this case the difference is 246 % compared to 70 %, when the protection needed increases from 910 m to 7.35 km.

Another aspect of the overestimation is that a min. distance of 62m, 281 m and 910 m will get the same protection, although 910m is 14 times larger then 62 m and three times larger then 281 m. Thus, the 1 km X 1 km grid size is not optimal for low protection distances.

For a fixed device considering the co-channel protection of 7.35 km the using a 1 km X 1km grid is sufficient. But for lower value a lower grid size should be used to avoid protecting areas not needing protection. The evaluation in this thesis is for both the 100m W and the 4 W CR devices, thus the 100 x100 m grid size is considered the appropriate choice. Using this size will result in the lowest overprotection value of upto 75 % for min. distance of 62 m. In addition it enables the method to separate the protection needed between 62 m, 281 m and 910 m. On the other hand such detailed information will increase the data storage needed. The stored data increases with 100 % when changing from a 100mx100x grid size to 1km x 1km grid size, but this is regarded acceptable to be able to decrease the overestimation.

9.2 Co-channel and adjacent channel C/I levels

In the concept evaluated in this thesis there is an underlying assumption that several CR device can operate simultaneously in the areas surrounding the TV receivers. According to Rachita et al., the outage probability at the TV receiver will increase when

Table 9.1: The protection given for varying grid size

Grid size	P_t **= 4 W, N= 17,** co-channel	P_t **= 100 mW, N= 3**, cochannel	P_t **= 100 mW, N= 3**, adjacent-channel
Protection distance	7.35 km	910 m	62 m
Area of protection: $r^2 * \pi$	169.7 km^2	2.6 km^2	0.012 km^2
100m	228 km^2	4.41 km^2	0.09 km^2
250 m	232.56 km^2	5.06 km^2	0.56 km^2
1 km	289 km^2	9 km^2	9 km^2

several CR device operate close to a TV receiver especially at the edge of a service area where the signal strength is assumed low [42]. The C/I ratio used which was defined by Ofcom [section 3.5], considers co-channel and adjcaent channel interference that may be present simultaneously. Thus the level chosen is considered sufficient.

But in addition, the overestimation given through the 1km x 1 km grid size, makes the method applicable even if the C/I ratio requirment is increased.

- For instance it is calculated in this section that the protection given by using the protection degree N= 17, corresponds to C/I =34 dB. Thus, the 33 dB C/I ratio can increase with 1 dB without changing the result of this thesis. This is the result of the overprotection done by using 1 km grid size. It is calculated that this extra buffer gives an approximately allowed increase of 1 dB for the C/I ratio requirement considering the co-channel usage. And an maximum increase between 4- 19 dB depending on the CR device.

In this thesis the protection degree of N= 3 and N= 17 is calculated, these levels as mentioned in the previous section corresponds to a min. protection distance of 1 km and 8 km.

In chapter 6 the method chosen to calculate the min. distance is reviewed. By using the C/I ratios requirement and using the Okumura Hata model, the min distance needed for the 4 W and the 100 mW devices was calculated.

If the method in chapter 6 is used in reverse, the C/I ratio corresponding to 1 km and 8 km can be calculated as seen in eq. 9.1.

$$L_{max} = E_{tCR}[dB\mu V/m] - E_{rCR}[dB\mu V/m]$$

$$E_{rcr} = E_{rtv} - S/I$$

Table 9.2: Maximum C/I increased allowed without affecting result when using 1kmx1km grids, considering the 4W CR device

	Co-channel C/I ratio	Adjacent channel C/I ratio
E_{rtv} E_{tCR}	$50 dB\mu V/m$ $140,8 dB\mu V/m$	$50 dB\mu V/m$ $140,8 dB\mu V/m$
pathloss L,using Hata model C/I corresponding to 1km C/I defined by Ofcom	125 $34,2$ 33 dB	$93,24$ $2,44$ -17 dB
C/I increase	1,2 dB	19,44 dB

$$S/I = E_{rtv} - E_{tCR} + L \tag{9.1}$$

For N= 17, the protection distance given is 8 km. Using the Okumura Hata model found in figure 6.3 for a 4 W CR device, it is found that a distance of 8 km corresponds to a path loss L=125. Using eq. 10.1, this corresponds to a C/I ratio of:

$S/I = 50[dB\mu V/m] - 140.8[dB\mu V/m] + 125 = 34.2dB$

Meaning that the protection achieved by using a 1 km X 1km grid allows the co-channel requirement to increase with 1,2 dB without this affecting the result of this thesis.

For N=3, the protection given is 1 km. Using the Okumura Hata model, at 1 km the upper curve give a path loss value of 93.24. The lower curve is defined for the 4 W device which results in a field strength of 140.8 dByV/M. Thus

$S/I = 50[dB\mu V/m] - 140.8[dB\mu V/m] + 93.24 = 2,44dB$

Thus, the C/I ratio considering adjacent channel interference of -17 dB can increase to 2.44 dB without it affecting the result of this thesis. The corresponding C/I ratios, and the maximum increases in C/I value that can be made without changing the result of this thesis are found in table 9.3 and 9.2.

Summary

This chapter has shown the major consequences of using a 1 km X 1km grid size and the advantages.

It is found that a 100x100 grid size is the most appropriate to represent the range of protection distance from 62m - 7.35 km. But the price to pay is an increase in the needed data storage.

Table 9.3: Maximum C/I increased allowed without affecting result when using 1kmx1km grids, considering the 100mW CR device

	Co-channel C/I ratio	Adjacent channel C/I ratio
E_{rtv}	$50dB\mu V/m$	$50dB\mu V/m$
E_{tCR}	$124,8dB\mu V/m$	$124,8dB\mu V/m$
pathloss L, using Hata model	$109,5$	$109,5$
C/I corresponding to 1km	34.2	$-12,8$dB
C/I defined by Ofcom	33 dB	-17 dB
C/I increase	1.7 dB	4,2 dB

The use of the 1 km X 1km grids in this thesis has its advantages because it adds an extra buffer considering the C/I ratio. The C/I ratio can increase between 4-19 dB considering the adjacent channel requirement, and with 1 dB considered the co-channel requirments without it affecting the Gray Space found in this thesis.

This is an advantage, as there are TV receivers at the edge of the TV service area with low TV signal. They are at more risk of experiencing interference, especially when several CR devices are operating in nearby locations.

10 Conclusion and future work

In this chapter the thesis is summarized. First, the major statements made in this thesis are presented, than a summary on the method used is conducted, and finally the TX database and RX database are compared.

10.1 Conclusion

In this thesis the Gray Space amount within the TV broadcasting band was investigated by registering TV receiver antennas. It is shown that there are large amount of Gray Space that are not utilized, which if utilized can benefit both the license-holder and application provider.

In Vinje the Gray Space consists in average of 96MHz for the 4 W device and increases to 115 MHz when considering the 100 mW CR device.

The use of frequencies that are licensed for TV broadcasting services are ineffective, thus should be opened to be utilize by other services. By implementing the RX database additional amount of unused frequencies are made available.

This section present the major statements made regarding the result of this thesis, and then a comparison between the TX database and RX database is done.

Statements :

- In section 8.3.8, it is stated that the Gray Space amount in Vinje increase between 64-96 MHz depending on the knowledge levels for 90 % of the locations, when the 4 W device is considered. For the 100 mW device there are 120 MHz Gray Space for 90 % of the locations, and at 70 % of the locations the whole spectrum is available.
- In section 8.3.9, it is concluded that the Gray space amount is considered as an excellent spectrum resource for low power devices like the 100 mW CR device. Because there are significant amount of Gray Space and there are households at those location that can utilize the Gray Space, making it appropriate to be used for in- home application. For a CR device needing higher capacity over a longer

time period as the IEEE 802.22, the Gray Space amount is considered appropriate to be used as additional spectrum. For instance, times when higher capacity is needed.

- In section 8.3.9, it is concluded that Knowledge level 2 is the level that is the most desirable when considering complexity, Gray Space amount, and the range of application that it enable to be implemented. But more research on the privacy aspect both for the household and the broadcasters is needed.
- In section 8.4.3, it is stated that the method and results calculated in this thesis is appropriate to represent the Gray Space amount found in Norway. But areas with high population density compared to land area are expected to have a decrease in the amount of Gray Space. Here the decrease in average was 15 MHz and 6 MHz for Lillehammer compared to Vinje, for CR device with transmit power of 4 W and 100mW, respectively.
- In chapter 9, an evaluation is done on variables affecting the result; Grid size and change in C/I ratio levels. A C/I ratio of 33 dB and -17 dB is used considering co-channel and adjacent channel interference, respectively. The method used allows an increase in the range of 4-19 dB considering the adjacent channel requirement, depending on the CR device. And with 1 dB considering the co-channel requirment for both CR device evaluated.

The RX database which results in additional usable frequencies is based on the registration on fixed devices. Thus, mobile TV receivers, microphones using the TV broadcasting band and cable head ends are not taken to account. Further research is needed for these aspects to be considered.

10.2 Summary of method

The amount of locations within three selected areas in Norway that can utilize the Gray Space was investigated. The areas are Vinje-, Tynset- and Lillehammer municipal. Today the research is focused on registering TV- transmitter information and then giving protection to all possible TV receivers within the TV service area, but by considering the actual TV receiver location a better mapping of the unused frequencies within the service area may be achieved.

The amount of locations containing Gray Space and the amount of Gray Space found are calculated, and how this result changes for different knowledge level are analyzed. The knowledge levels are:

- KN1: Knowing the TV receiver position and the available channels at a location

- KN2: Knowing TV receiver location and which broadcaster a household is subscribing to
- KN3: Knowing TV receiver location and actual TV usage in time

At each area information on population density was used to find possible amount of TV receiver locations. "The unused locations" are locations were the adjacent channel or/and co-channels can be reused by a Cognitive device without disturbing the TV receiver.

Two types of Cognitive radio device are considered , one having a transmit power of 100 mW and the other having a transmit power of 4W. The 4W CR device represents a transmitter providing broadband access, like the IEEE 802.22. And the portable device may have diverse application areas both in- home and outdoor.

The amount of Gray Space found at those locations will vary depending the Cognitive radio transmit power.

For high transmit power devices there is less Gray Space than for low transmit power devices, because they can be put closer to the TV receiver thus are able to utilize more of the unused frequencies. For instance, for the result in Vinje there is an average deviation of 20 MHz when evaluated the 4 W device compared to the 100mW CR device.

Knowledge level

For the method of this thesis to be implemented one needs a method of delivering the TV receiver location and channel usage to the database, either using an IP connection as this thesis assumes or through the TV receiver owner. The knowledge levels are compared in section 8.3.9, and summarized her.

- Knowledge level 1 was discussed as the easiest to implement, needing only TV receiver location and information on the channels available at those locations. No sensitive information is used, on the other hand the method does not allow in-home application because all household are protected.
- Knowledge 2 demands information on location and which subscriber a Television owner is using. As mention this is business sensitive information when considering both the broadcasters and the households, but the profit and services that can be gained by utilizing the unused frequencies makes this an interesting opportunity. This level is the one chosen as the most appropriate when comparing complexity, available Gray Space amount and the range of application that can be provided.
- For knowledge level 3 a more comprehensive system is required because the information must be real time but the Gray Space amount retrieved is larger for this level. More research is needed on this field to be able to implement KN3.

10.3 Comparing the methods

The goal of the thesis was to show how the unused location and unused frequencies with focus on the Gray Space amount changes when we use the TV receiver information. The result of Gray Space is summaries in section 8.3.8 for Vinje municipal and in section 8.4.3 the other areas are considered.

- Today: at each area the TV broadcasting band is not permitted to be used by a Cognitive radio device at any location. Thus the 430 MHz are utilized at 0 % of the locations, considering other service than for TV broadcasting.
- TX database: The TV transmitter information is used for this database as presented in chapter 3. We know that within the service area there is limits to co-channel and adjacent channel utilization, but other none adjacent channels may be used inside the service area. This usage will depend on information on other TV transmitters. In this thesis only TV signals from the TV transmitter delivering service at the area evaluated, and other TV transmitters in the same Signal Frequency Network(SFN) are evaluated thus this exact value can not be found. But a maximum of 200 MHz is calculated, which is found at all three areas. Thus, 200 MHz are assumed available at 100 % of the locations.
- RX database: Using TV receiver information one can utilize higher amount of the unused frequencies per location. This is the concept worked on in this thesis. The unused locations and Gray Space amount in Vinje are calculated in chapter 8, and also presented in table 10.1-2.

To give a better understanding of the result, only the result at Vinje municipal is presented and the amount of Gray Space for each knowledge level is presented.

Considering a Cognitive radio with 4 W transmit power:

For KN1, the maximum Gray Space found is 80 MHz at 40 % of the location, while the Gray Space amount is not defined for 90 % of the locations.

For KN2, the maximum level found increases to 120 MHz at 20 % of the location and at 90 % of the location the Gray Space amount is now defined as 64 MHz.

For KN3, the maximum Gray Space level is 112 MHz at 40 % of the locations for both timeperiods. For timeperiod 1 the same amount is also found at 70 % of the location. Time period 1 and 2 refer to 06:00 -09:00 and 20:00- 23:00. The Gray Space at 90 % of the locations decreases to 80-94 MHz depending on the time.

When the portable device is evaluated, it is seen that the unused location are the same but the Gray Space amount increases to 96- 120 MHz. Indicating that large part of the TV broadcasting band can be reused by a portable device, at 20 % of the locations the

Table 10.1: Result: White Space and Gray Space amount in Vinje: Considering a Fixed device

%	White space amount	KN1	KN2	KN3 time 1	KN3 time 2
20 %	200 MHz	80 MHz	120 MHz	112 MHz	112 MHz
40 %	200 MHz	80 MHz	88 MHz	112 MHz	112 MHz
70 %	200 MHz	-	80 MHz	112 MHz	96 MHz
90 %	200 MHz	-	64 MHz	96 MHz	80 MHz

Table 10.2: Result: White Space and Gray space amount in Vinje: Considering a portable device

%	White space amount	KN1	KN2	KN3 time 1	KN3 time 2
20 %	200 MHz	120 MHz	120 MHz	120 MHz	120 MHz
40 %	200 MHz	120 MHz	120 MHz	120 MHz	120 MHz
70 %	200 MHz	-	120 MHz	120 MHz	120 MHz
90 %	200 MHz	-	96 MHz	96 MHz	96 MHz

entire TV broadcasting band is available regardless of the knowledge level considered. This is also found for 70 % of the location when only considering KN2 and KN3.

In general when registering TV receiver information there is an average increase of 96 MHz, when considering a 4 W device and it increases to 115 MHz considering the 100 mW CR device. The result was similar in Tynset municipal, while in Lillehammer municipal it decreases to 81 MHz and 109 MHz considering a transmit power of 4W and 100 mW, respectively. The Gray Space amount are in addition to the White Space of 200 MHz.

TX database VS RX database

By registering TV receiver information:

- The method opens up the possibility to utilize additional unused frequencies that is overprotected by the TX database.

In addition to the increase in amount of unused frequencies:

- At some locations there may be TV receivers that need extra protection, this can easily be given when TV receiver information is registered. But is not possible with the TX database.
- As mentioned in chapter 3 there are users that are receiving TV signals but are not paying the license fee: by registering users a better control on who has the right

to receive TV service is given.

- Registering TV receivers enable us to exploit terrain variations and population density. The Gray Space in rural areas is larger then in urban areas, this can be exploited using the RX database. This was presented in section 4.3, in addition a scenario where the terrain was considered was discussed. Using the RX database will enable a greater analysis of the unused frequencies.

On the other hand the method demands more information to be stored in the database compared to the TX database that registers TV stations. In addition:

- It assumes that the TV receivers have a method of registering its location and channel usage, for instance by using an IP connection.
- As mention in chapter 5 the information on which broadcaster the household subscribe to is business sensitive. For knowledge level 2 and 3 to be implemented this information is needed.
- The amount of vacant channels may change depending on the users. The TV-receiver will always be the primary user of the TV band. If someone decides to install a TV-antenna at a location, the cognitive radio must ensure that it is not disturbed. If the unused frequencies are few, a system may not entirely rely on the Gray Space found. But as suggested the Gray Space may be used as a backup for services needing high capacity.

When comparing the above points, it is concluded that the advantages of making the Gray Space available is greater than the actions needed to implement the method.

As seen when registering TV receiver locations the true usage of the band is seen. And there are large amount of unused locations that contain frequencies, which can be utilized without disturbing the TV receivers. Though there are some disadvantages, the findings of this thesis show that the registration of TV receivers is a field giving value for all involved: for the broadcasters and application providers gaining a new source of income, and for the potential consumer who gain new services.

The statically location of TV receivers makes this an easy usage to register. Today households owning a TV set are already registered and little means need to be done to be able to register the protection that the household needs, such that the spectrum usage can be more effective.

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Appendices

.1 Matlab code

This section include the matlab code used for Vinje municipal. The code is similar when using the information on Tynset and Lillehammer municipal.

..

```
%1) Define Topology
%2) Knowledge level
    %A) No information on frequncey usage is used
    %B) Broadcaster
    %C) Time based
%3) Implement different protection degrees

disp('Vinje simulation')
%1) Define Topology and TV receiver locations

A = xlsread('VinjeData.xls');


% # of longitude elements
m= min(A(:,1));
mx= max(A(:,1));
y=  mx-m +1;


% # of latitude elements
m2= min(A(:,2));
mx2= max(A(:,2));
x=  mx2-m2 +1;


% convert longitude to matrise elementposition
yElement=zeros(1,y);% Y punktene med RX
xElement=zeros(1,x);

for i= 1:y

    yElement(i)= m;
   m= m+1 ;

end

for j= 1: x

    xElement(j)= mx2;
   mx2= mx2-1 ;
```

```
end


mainVinje= zeros(length(xElement), length(yElement));

% Mark possible TV receiver locations

for k= 1: length(A(:,1))
    A(k,1);
   A(k,2);
  mainX= find( xElement== A(k,2));
  mainY= find( yElement== A(k,1));

mainVinje(mainX,mainY)= 2;
end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%2)Choose RX for different knowledge levels
% Possible channel usage
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp('-----------------2)- Choose RX for different knowledge levels -------------- ')
disp(' A) Assuming all receiver are using all of the frequencies availible')
% A) all


%cropping the matrix to fit the topology:
mainVinje([1:15],[1:30])= NaN;
mainVinje([42:60],[1:15])= NaN;

figure('Name', 'Vinje')
imagesc(mainVinje)
colormap(Jet)
%colormap(flipud(bone))
%colorbar

% Protection  for different N
matrixSize = size(find(mainVinje==0)) + size(find(mainVinje==2)); % finding the new
amount of matrix elements after croping

noneProtectedlocations= protection(mainVinje,  matrixSize(1))

% save file: out.tex
rowLabels = { 'Number of none protected locations ', ' Percentage of the total area' };
columnLabels = {'N= 3' , 'N= 7' , 'N= 17' , 'N=29 ' };

matrix2latex(noneProtectedlocations, 'out.tex', 'rowLabels', rowLabels, 'columnLabels',
columnLabels, 'alignment', 'c', 'format', '%-6.2f', 'size', 'large');

----------------------------------------------------------------------
```

```
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Actual channel usage
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 rxPositions= length(A(:,1)); % the number of possible locations containing TV receivers

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp(' Broadcaster information Nrk- 98 %')
% NRK

% Define receiver information and position
percentageNrk=98; %persentage
nrkUsers= (rxPositions/ 100)*percentageNrk

[mainWithNrkUser, nrkUserPositionIndexV]= positionReceiversReal(nrkUsers,A, x,y, xElement,
 yElement);

%  % %Image:  The original matrix containing NRK users
%  figure('Name', 'Receiver locations for NRK users in Vinje')
%  imagesc(mainWithNrkUser)
%  colormap(Jet)
%  imagesc(mainWithNrkUser)
%  colormap(gray)
%  colormap(flipud(bone))
%  colorbar

% Protection for different N
 noneProtectedlocationNRK= protection(mainWithNrkUser,matrixSize2(1))

% Figure of RiksTV usage
 rikstv_p3([1:15],[1:30])= NaN;
 rikstv_p3([42:60],[1:15])= NaN;

 rikstv_p17([1:15],[1:30])= NaN;
 rikstv_p17([42:60],[1:15])= NaN;

 figure;imagesc(rikstv_p17)
colormap(flipud(bone))
figure;imagesc(rikstv_p3)
colormap(flipud(bone))




% skal lagre fil: kaller den out.tex
rowLabels = { 'Number of none protected locations ', ' Percentage of the total area' };
columnLabels = {'N= 3' , 'N= 7' , 'N= 17' , 'N=29 ' };
```

```
matrix2latex(noneProtectedlocationNRK, 'outNrk.tex', 'rowLabels', rowLabels,
'columnLabels', columnLabels,'alignment', 'c', 'format', '%-6.2f', 'size', 'large');

% # of household at those locations
% for fixed
%N=3;
%[amountOf_Household_P3, totUnusedlocation_P3,new_P3 ]= evaluateValueOfResult(mainVinje,
% mainWithNrkUser, N);

% for portable
%N=17;
%[amountOf_Household_P17, totUnusedlocation_P17,new_P17 ]= evaluateValueOfResult(mainVinje,
%mainWithNrkUser, N);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp('2)- Broadcaster information RiksTV- 15%')
% RiksTV

% Define receiver information and position
 percentageRikstv=15; %persentage
 rikstvUsers= (rxPositions/ 100)*percentageRikstv

 % find 22 % of the receiver at Vinje:
 [mainWithRikstvUsers, rikstvUserPositionIndexV]= positionReceiversReal(rikstvUsers,A, x,y,
 xElement, yElement);

%  % % Image:  The original matrix containing riksTV users
% figure('Name', 'Receiver locations for RiksTV users at Vinje')
% imagesc(mainWithRikstvUsers)
% colormap(gray)
% colormap(flipud(bone))
% colorbar

% Protection for different N
noneProtectedlocationsRIKSTV= protection(mainWithRikstvUsers,matrixSize2(1))

 % skal lagre fil: kaller den out.tex
rowLabels = { 'Number of none protected locations ', ' Percentage of the total area' };
columnLabels = {'N= 3' , 'N= 7' , 'N= 17' , 'N=29 ' };

matrix2latex(noneProtectedlocationsRIKSTV, 'outRiksTV.tex', 'rowLabels', rowLabels,
'columnLabels', columnLabels, 'alignment', 'c', 'format', '%-6.2f', 'size', 'large');

%N=3;
%[amountOf_Household_P3_rikstv, totUnusedlocation_P3_rikstv,new_P3_rikstv ]=
%evaluateValueOfResult(mainVinje,mainWithRikstvUsers, N);

% for portable
```

```
%N=17;
%[amountOf_Household_P17_rikstv, totUnusedlocation_P17_rikstv,new_P17_rikstv ]=
%evaluateValueOfResult(mainVinje, mainWithRikstvUsers, N);


------------------------------------------------------------------------------------------

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Time based channel usage
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 disp('-----------------C)-Information based on time------------- ')
 % Time- period 1: 29.6, 3, 4.7
 % Time- period 2: 41.9, 10.4, 9.6


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Time period 1
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Mux1 29.6 %/ 98 % NRK users
percentageActiveNRK=  29.6;
activeNrkUsers_t11= (nrkUsers/ 100)*percentageActiveNRK

[mainWithActiveNrKUser_t11]= receiversForTimeBasedInfo(nrkUserPositionIndexV,
activeNrkUsers_t11, xElement, yElement, x,y, A);


 %%%%%%%%%%%%%%%%%%%%%%%%%%%
 % Mux3 3%/22 % RiksTV users
 percentageActiveRiksTV13=  3;
 activeRikstvUsers_t13= (rikstvUsers/ 100)*percentageActiveRiksTV13

[mainWithActiveRikstvUsers_t13]= receiversForTimeBasedInfo(rikstvUserPositionIndexV,
activeRikstvUsers_t13, xElement, yElement, x,y, A);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Mux4 4.7/ 22 % RiksTV users
 percentageActiveRiksTV14=  4.7;
 activeRikstvUsers_t14= (rikstvUsers/ 100)*percentageActiveRiksTV14

[mainWithActiveRikstvUsers_t14]=receiversForTimeBasedInfo( rikstvUserPositionIndexV,
activeRikstvUsers_t14, xElement, yElement, x,y, A);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sumTime1Rikstv=  mainWithActiveRikstvUsers_t13 + mainWithActiveRikstvUsers_t14;
sumTime1Rikstv(sumTime1Rikstv>2)=2;
```

```
matrixSize2 = size(find(mainVinje==0)) + size(find(mainVinje==2));
% result for Rikstv MUX
[noneProtectedlocations_t1_rikstv, time1rikstv_p3, time1rikstv_p17]
= protection(sumTime1Rikstv,matrixSize2(1));

% Result for NRK MUX
[noneProtectedlocations_t1_nrk, time1nrk_p3, time1nrk_p17]=
protection(mainWithActiveNrKUser_t11, matrixSize2(1));


%image
figure('Name', 'Time-period 1: Locations for receivers using MUX 1, 3 and 4')
subplot(2,2,1),subimage(mainWithActiveNrKUser_t11)
colormap(gray)
colormap(flipud(bone))

subplot(2,2,2), subimage(mainWithActiveRikstvUsers_t13)
colormap(gray)
colormap(flipud(bone))

subplot(2,2,3), subimage(mainWithActiveRikstvUsers_t14)
colormap(gray)
colormap(flipud(bone))

% save location info: outTime1rikstv.tex
rowLabels = { 'Number of none protected locations ', ' Percentage of the total area' };
columnLabels = {'N= 3' , 'N= 7' , 'N= 17'  };

matrix2latex(noneProtectedlocations_t1_rikstv, 'outTime1rikst.tex',
'rowLabels', rowLabels, 'columnLabels', columnLabels, 'alignment', 'c',
 'format', '%-6.2f', 'size', 'large');

% save location info: outTime1nrk.tex
rowLabels = { 'Number of none protected locations ', ' Percentage of the total area' };
columnLabels = {'N= 3' , 'N= 7' , 'N= 17'  };

matrix2latex(noneProtectedlocations_t1_nrk, 'outTime1nrk.tex', 'rowLabels',
owLabels, 'columnLabels', columnLabels, 'alignment', 'c', 'format', '%-6.2f',
'size', 'large');



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Time period 2
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Mux1 41.9
percentageActiveNRK2=  41.9;
```

```
activeNrkUsers_t21= (nrkUsers/ 100)*percentageActiveNRK2;

[mainWithActiveNrKUser_t21]= receiversForTimeBasedInfo(nrkUserPositionIndexV
,activeNrkUsers_t21, xElement, yElement, x,y, A);

% Protection for different N
%noneProtectedlocationsNrKUser_t21= protection(mainWithActiveNrKUser_t21)

% Mux3 10.4
percentageActiveRiksTV2=  10.4;
activeRikstvUsers_t23= (rikstvUsers/ 100)*percentageActiveRiksTV2;

[mainWithActiveRikstvUsers_t23]= receiversForTimeBasedInfo(rikstvUserPositionIndexV,
activeRikstvUsers_t23, xElement, yElement, x,y, A);

% Protection for different N
%noneProtectedlocationsRikstvUsers_t23= protection(mainWithActiveRikstvUsers_t23)

% Mux4 9.6
percentageActiveRiksTV24=  9.6;
activeRikstvUsers_t24= (rikstvUsers/ 100)*percentageActiveRiksTV24;

[mainWithActiveRikstvUsers_t24]= receiversForTimeBasedInfo(rikstvUserPositionIndexV,
activeRikstvUsers_t24, xElement, yElement, x,y, A);

% Protection for different N
%noneProtectedlocationsRikstvUsers_t24= protection(mainWithActiveRikstvUsers_t24)


sumTime2Rikstv=  mainWithActiveRikstvUsers_t23 + mainWithActiveRikstvUsers_t24;
sumTime2Rikstv(sumTime2Rikstv>2)=2;

% result for Rikstv MUX
[noneProtectedlocations_t2_rikstv, time2rikstv_p3, time2rikstv_p17]=
protection(sumTime2Rikstv,matrixSize2(1));

% Result for NRK MUX
[noneProtectedlocations_t2_nrk, time2nrk_p3, time2nrk_p17]=
protection(mainWithActiveNrKUser_t21,matrixSize2(1));


%image
figure('Name', 'Locations for receivers using MUX 1, 3 and 4 at time 2')
subplot(2,2,1),subimage(mainWithActiveNrKUser_t21)
colormap(gray)
colormap(flipud(bone))

subplot(2,2,2), subimage(mainWithActiveRikstvUsers_t23)
colormap(gray)
colormap(flipud(bone))
```

```
subplot(2,2,3), subimage(mainWithActiveRikstvUsers_t24)

colormap(gray)
colormap(flipud(bone))


% save location info: outTime2rikstv.tex
rowLabels = { 'Number of none protected locations ', ' Percentage of the total area' };
columnLabels = {'N= 3' , 'N= 7' , 'N= 17'  };

matrix2latex(noneProtectedlocations_t2_rikstv, 'outTime2rikst.tex',
'rowLabels', rowLabels, 'columnLabels', columnLabels, 'alignment', 'c', 'format',
'%-6.2f', 'size', 'large');

% save location info: outTime2nrk.tex
rowLabels = { 'Number of none protected locations ', ' Percentage of the total area' };
columnLabels = {'N= 3' , 'N= 7' , 'N= 17'  };

matrix2latex(noneProtectedlocations_t2_nrk, 'outTime2nrk.tex', 'rowLabels',
 rowLabels, 'columnLabels', columnLabels, 'alignment', 'c', 'format', '%-6.2f',
'size', 'large');
```

.1.1 Function Protection

The function protection is called to mark the surrounding N elements as "protected". We want the NXN protetion area that correspond km protection off:1km and 8km =¿ NXNArea= 3 and 17

..

```
function[noneProtected, output3, output17]= protection(mainMatrix,matrixSize)


noneProtected(2,3)=0;

kernel3(3, 3)= 0;
kernel3(:,:)= 4;
output3 = conv2(mainMatrix, kernel3, 'same');
%Replace everything with 4
```

```
output3(output3>4)=4;
output3(mainMatrix == 2) = 2;

output3([1:15],[1:30])= 1000;
output3([42:60],[1:15])= 1000;

% Count none protected locations
 i=1;
 noneProtected(1,i)= count(output3);
 %noneProtected(2,i)= noneProtected(1,i)/(x*y);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
kernel7(7, 7)= 0;
kernel7(:,:)= 4;
output7 = conv2(mainMatrix, kernel7, 'same');
%Replace everything with 200
output7(output7>4)=4;
output7(mainMatrix == 2) = 2;

output7([1:15],[1:30])= 1000;
output7([42:60],[1:15])= 1000;

 % Count none protected locations
 i=i+1;
 noneProtected(1,i)= count(output7) ;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
kernel17(17, 17)= 0;
kernel17(:,:)= 4;
output17 = conv2(mainMatrix, kernel17, 'same');
%Replace everything with 4
output17(output17>4)=4;
output17(mainMatrix == 2) = 2;

output17([1:15],[1:30])= 1000;
output17([42:60],[1:15])= 1000;

 % Count none protected locations
 i=i+1;
 noneProtected(1,i)= count(output17);
 noneProtected(2,:)= (noneProtected(1,:)/(matrixSize))*100;

end
```

.1.2 Function positionReceiversReal and function receiversForTimeBasedInfo

These function are called to chooses the right amount of receivers from the total household locations and then choose random locations within the Topology.

```
function[randUserPosition,userPositionIndex]= positionReceiversReal
(users,A, x,y, xElement, yElement)

%
usersN= round(users)
userPositionIndex= randi(length(A),[1,usersN]);

% defines an array as larges as the original topology
randUserPosition(x,y) = 0;
randUserPosition(:,:) = 0;

% Positions the new amount of receiver in the topology
for j= 1: length(userPositionIndex)
  A(userPositionIndex(j),1); % y 100, 100, 101
  A(userPositionIndex(j),2); % x 6622, 6626, 6626
  mainX=  xElement== A(userPositionIndex(j),2);
  mainY=  yElement== A(userPositionIndex(j),1);

randUserPosition(mainX,mainY)= 2;
end
```

```
function[activeUserPosition]= receiversForTimeBasedInfo
(possibleUserPositionsIndex,activeUsers, xElement, yElement,x,y, A)

% positions receivers
possibleActiveUserPositions= randperm(length(possibleUserPositionsIndex));

activeUserPosition(x,y) = 0;
activeUserPosition(:,:) = 0;

for j= 1:activeUsers

A(possibleActiveUserPositions(j),1);
A(possibleActiveUserPositions(j),2);

mainX=  xElement== A(possibleActiveUserPositions(j),2);
mainY=  yElement== A(possibleActiveUserPositions(j),1);
activeUserPosition(mainX,mainY)= 2;

end
```

```
end

end
```

.1.3 Function FindSum

This function is used to sum the amount of location and Gray Space for each knowledge level.

```
disp('----------------------KN1----------------------')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Possible channel usage, co-channel 40 MHz and 80 MHz adj ch.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%sumFixed; all_p17 :co-channel:42MHz, all_p3: adjacent ch:72MHz
sumKN1_Fixed= sumFreq4(all_p17, 40, all_p3, 80);

%sumPortable; 2* all_p3: co- and adjacent channels: 114 MHz.
sumKN1_Portable= sumFreq4(all_p3, 40, all_p3, 80);

% Find the range of frequency amount and the count those=> find percentage
% of the total area
numberOfUniqueKN1_fixed= unique(sumKN1_Fixed)
numberOfUniqueKN1_portable= unique(sumKN1_Portable)

[percentFixed_KN1, percentPortable_KN1]= findpercent4(mainTynset, sumKN1_Fixed,
numberOfUniqueKN1_fixed ,sumKN1_Portable, numberOfUniqueKN1_portable,
 matrixSize(1))

disp('----------------------KN2----------------------')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Actual channel usage
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%
% Sum NRK
%Fixed- amount of frequencies considering nrk protection
sumNrk= sumFreq4(nrk_p17, 8 ,nrk_p3, 16);

%portable
sumNrk_Portable= sumFreq4(nrk_p3, 8, nrk_p3, 16);

%%%%%%%%%%%%
% Sum rikstv
%Fixed- amount of frequencies considering rikstv protection
sumRikstv= sumFreq4(rikstv_p17, 32 ,rikstv_p3, 64);
```

```
%Portable
sumRikstv_Portable= sumFreq4(rikstv_p3, 32,rikstv_p3, 64);

%%%%%%%%%%%%
% sum both for fixed and adj.

%Amount of availale frequencies for Fixed & Portable
sumKN2_Fixed= sumNrk + sumRikstv;
sumKN2_Portable= sumNrk_Portable + sumRikstv_Portable;

% Find the range of frequency and count those=> find percentage
% of the total area
numberOfUniqueKN2_fixed= unique(sumKN2_Fixed);
numberOfUniqueKN2_portable= unique(sumKN2_Portable);

[percentFixed_KN2, percentPortable_KN2]= findpercent4(mainTynset, sumKN2_Fixed,
 numberOfUniqueKN2_fixed ,sumKN2_Portable, numberOfUniqueKN2_portable,
matrixSize(1))


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Time based
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp('---------------------Time 1---------------------')
%%%%%%%%%%
%Time 1
%%%%%%%%%%
% Sum Nrk
%Fixed- amount of frequencies considering nrk protection
sumNrk_t1= sumFreq4(time1nrk_p17, 8 ,time1nrk_p3, 16);
%
%portable
 sumNrk_Portable_t1= sumFreq4(time1nrk_p3, 8, time1nrk_p3, 16);

%%%%%%%%%%%%
% Sum rikstv
%Fixed- amount of frequencies considering rikstv protection
 sumRikstv_t1= sumFreq4(time1rikstv_p17, 32 ,time1rikstv_p3, 64);

%Portable
sumRikstv_Portable_t1= sumFreq4(time1rikstv_p3, 32,time1rikstv_p3, 64);

%%%%%%%%%%%%
% sum both for fixed and adj.

%Amount of availale frequencies for Fixed & Portable
 sumKN3_Fixed_t1= sumNrk_t1 + sumRikstv_t1;
 sumKN3_Portable_t1= sumNrk_Portable_t1 + sumRikstv_Portable_t1;

% Find the range of frequency amount and the count those=> find percentage
```

```
% of the total area
numberOfUniqueKN3_fixed_t1= unique(sumKN3_Fixed_t1);
numberOfUniqueKN3_portable_t1= unique(sumKN3_Portable_t1);

[percentFixed_KN3_t1, percentPortable_KN3_t1]= findpercent4(mainTynset,
sumKN3_Fixed_t1, numberOfUniqueKN3_fixed_t1 ,sumKN3_Portable_t1,
numberOfUniqueKN3_portable_t1, matrixSize(1))


disp('----------------------Time 2---------------------')

%%%%%%%%%%%%
% Time2
%%%%%%%%%%
% Sum Nrk
%Fixed- amount of frequencies considering nrk protection
 sumNrk_t2= sumFreq4(time2nrk_p17, 8 ,time2nrk_p3, 16);

%portable
 sumNrk_Portable_t2= sumFreq4(time2nrk_p3, 8, time2nrk_p3, 16);

%%%%%%%%%%%%%%
% Sum rikstv
%Fixed- amount of frequencies considering rikstv protection
 sumRikstv_t2= sumFreq4(time2rikstv_p17, 32 ,time2rikstv_p3, 64);

%Portable
sumRikstv_Portable_t2= sumFreq4(time2rikstv_p3, 32,time2rikstv_p3, 64);

%%%%%%%%%%%%
% sum both for fixed and adj.

%Amount of availale frequencies for Fixed & Portable
 sumKN3_Fixed_t2= sumNrk_t2 + sumRikstv_t2;
 sumKN3_Portable_t2= sumNrk_Portable_t2 + sumRikstv_Portable_t2;
%

% Find the range of frequency amount and the count those=> find percentage
% of the total area
numberOfUniqueKN3_fixed_t2= unique(sumKN3_Fixed_t2);
numberOfUniqueKN3_portable_t2= unique(sumKN3_Portable_t2);

[percentFixed_KN3_t2, percentPortable_KN3_t2]= findpercent4(mainTynset,
sumKN3_Fixed_t2, numberOfUniqueKN3_fixed_t2 ,sumKN3_Portable_t2,
numberOfUniqueKN3_portable_t2, matrixSize(1))



function[sum]=sumFreq4(co_matrix, co_amount, ad_matrix, ad_amount)
% Adding with NaN is complicated to implement, thus the locaiton are given
```

```
% another number.

co_matrix([1:15],[1:30])= 1000; co_matrix([42:60],[1:15])= 1000;
ad_matrix([1:15],[1:30])= 1000; ad_matrix([42:60],[1:15])= 1000;

% unused locations are set equal to the amount of frequency they consist of
co_matrix(co_matrix==0)=co_amount;
% TV receiver locations and protection areas are set as 0.
co_matrix(co_matrix< 5)= 0;


ad_matrix(ad_matrix==0)= ad_amount;
% TV receiver locations and protection locations are set to 0.
ad_matrix(ad_matrix<5)= 0;


%Sum the available frequencies at each location
sum=co_matrix +ad_matrix;

end

function [uniqueFixed,uniquePortable]= findpercent4(mainVinje, fixedmatrix,
uniqueFixed, portablematrix, uniquePortable, matrixSize)

% for fixed device
for l= 1:length(uniqueFixed)

amountOFlocation= size(find(fixedmatrix==uniqueFixed(l)));

uniqueFixed(l,2)= amountOFlocation(1);
uniqueFixed(l,3)= (uniqueFixed(l,2)/(matrixSize))*100;

numberHouseholds= size(find(fixedmatrix== uniqueFixed(l)& mainVinje==2));
uniqueFixed(l,4)= numberHouseholds(1);

end


% for portable device
for n= 1:length(uniquePortable)

amountOFlocations= size(find(portablematrix==uniquePortable(n)));

uniquePortable(n,2)= amountOFlocations(1);
uniquePortable(n,3)= (uniquePortable(n,2)/(matrixSize))*100;

numberHousehold= size(find(portablematrix== uniquePortable(n)& mainVinje==2));
uniquePortable(n,4)= numberHousehold(1);

end
```

```
end
```

.2 Simulation method

This section expands the results presented in section 8.4 for the other areas, which were Tynset and Lillehammer municipal.

.2.1 Crop the matrix to fit Area of Vinje, Lillehammer and Tynset

The method used when converting the area of the Topology will expand the original. In this section the method used to crop the matrix to fit the original area is described.

For Vinje there are 734 ekstra element size that is not located in Vinje municipal. Thus 735 matrix elements are marked as not belonging to the area, by putting those elements equal to NaN. A parameter in Matlab that stands for Not a Number. Thus, when calculating those locations are not taken to account. For Lillehammer 178 matrix elements sized are marked as Nan, and at Tynset 1195 elements are marked. Figure .1, .3 and .2 shows were those areas are marked as black matrix elements. These location are not included when calculating unused locations.

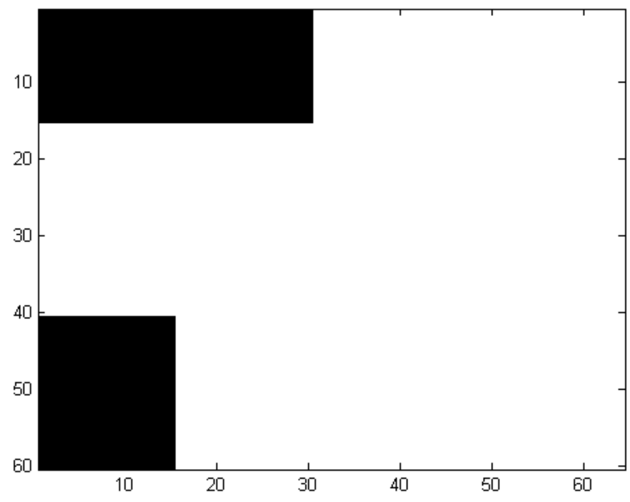


Figure .1: Locations marked as being outside Vinje

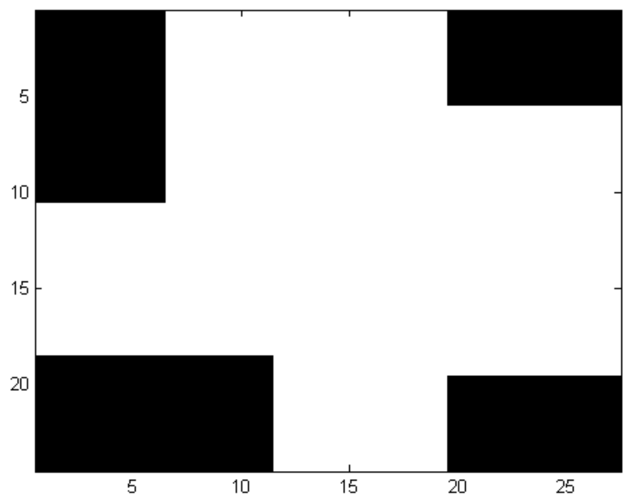


Figure .2: Locations marked as being outside Lillehammer

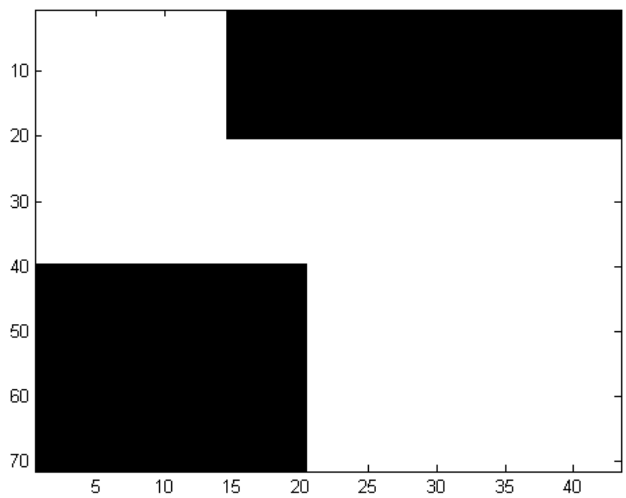
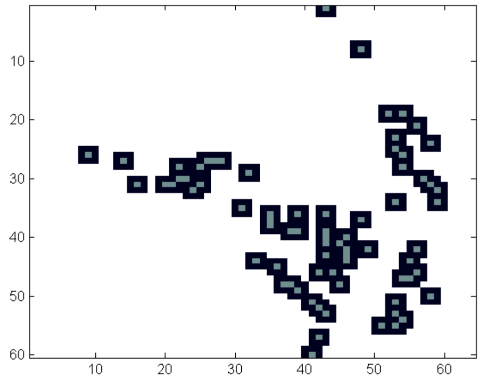
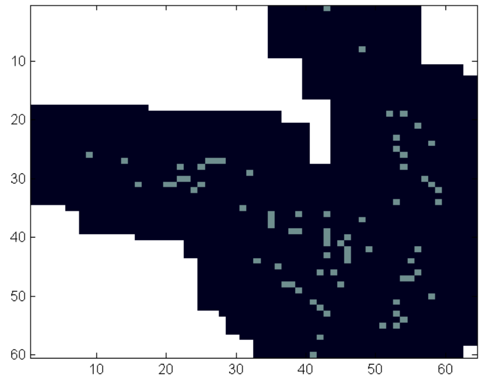


Figure .3: Locations marked as being outside Tynset



(a) Protection corresponding to 62m and 281 m



(b) Protection corresponding to 7,35 km

Figure .4: KN3, time 1 for MUX 2, 3, 4 and 5. Unused locations in Vinje for protection degree N= 3 and N= 17

.3 Vinje

The colormap showing the location with Gray Space for knowledge level 3 is found in table .4 and .5. This is an extention of the result in section 8.3.9.

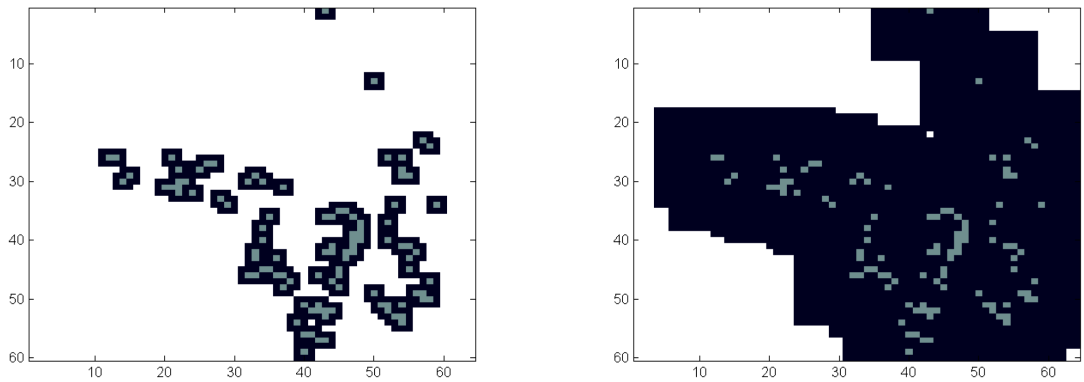
.4 Tynset

In this section the tables containing detailed result for the amount for Grey and White space for each knowledge level in Tynset are presented.

KN 1: all 5 MUX'es	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	1323.00	703.00	49.00
Percentage of the total area	70.64	37.53	2.62

KN 2: MUX 2, 3, 4 and 5	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	1721.00	1356.00	457.00
Percentage of the total area	91.88	72.40	24.40

KN 2: MUX 1	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	1484.00	1002.00	427.00
Percentage of the total area	79.23	53.50	22.80



(a) Protection corresponding to 62m and 281 m

(b) Protection corresponding to 7,35 km

Figure .5: KN3, time 2 for MUX 2, 3, 4 and 5. Unused locations in Vinje for protection degree N= 3 and N= 17

Figure .6: Channel usage of the strongest TV transmitter in Tynset: ch. 23, 26, 34, 40, 49

Table .3: Knowledge level 1, Tynset:The amount of Grey space for a **4 watt Fixed device**

Frequency amount	Amount of location	distinctly found at % of locations	total percentage of location	household locations
80 MHz	1274	68 %	70.6 %	0
120 MHz	49	2.6 %	2.6 %	0

Table .4: Knowledge level 1, Tynset:The amount of Grey space for a **100mW portable device**

Frequency amount	Amount of location	Percentage of location	household locations
120 MHz	1323	70.6 %	0

Time- period 1, MUX 1	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	1616.00	1190.00	475.00
Percentage of the total area	86.28	63.53	25.36

Time- period 1, MUX 2 ,3 ,4 and 5	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	1864.00	1824.00	1618.00
Percentage of the total area	99.52	97.38	86.39

Time- period 2, MUX 1	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	1551.00	1016.00	374.00
Percentage of the total area	82.81	54.24	19.97

Time- period 2, MUX 2 ,3 ,4 and 5	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	1846.00	1768.00	1544.00
Percentage of the total area	98.56	94.39	82.43

Table .5: Knowledge level 2, Tynset:The amount of Grey space for a **4 W fixed device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
16 MHz	16	0.9 %	92.7%	71
64 MHz	253	13.5 %	91.9 %	70
80 MHz	944	50.4 %	78.4 %	4
88 MHz	67	3.6 %	28 %	1
112 MHz	97	5.2 %	24.4 %	1
120 MHz	360	19.2 %	19.2 %	0

Table .6: Knowledge level 2, Tynset:The amount of Grey space for a **100mW portable device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
24 MHz	16	0.9 %	92.7 %	71
96 MHz	253	13.5 %	91.9 %	70
120 MHz	1468	78.4 %	78.4 %	4

Table .7: Knowledge level 3.1, Tynset:The amount of Grey space for a **4 W fixed device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
16 MHz	5	0.3 %	99.8 %	150
64 MHz	31	1.7 %	99.5 %	149
80 MHz	200	10.7 %	97.9 %	134
88 MHz	15	0.8 %	87.2 %	126
96 MHz	222	11.9 %	86.4 %	125
112 MHz	936	50 %	74.5 %	33
120 MHz	460	24.6 %	24.6 %	1

Table .8: Knowledge level 3.1, Tynset:The amount of Grey space for a **100mW portable device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
24 MHz	5	0.3 %	99.8 %	150
96 MHz	253	13.5 %	99.5 %	149
120 MHz	1611	86 %	86 %	42

Table .9: Knowledge level 3.2, Tynset:The amount of Grey space for a **4 W fixed device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
64 MHz	54	2.9 %	98.6 %	140
80 MHz	248	13.2 %	95.7 %	123
96 MHz	241	12.9 %	82.4 %	122
112 MHz	929	49.6 %	69.9 %	12
120 MHz	374	20 %	20 %	0

Table .10: Knowledge level 3.2, Tynset :The amount of Grey space for a **100mW portable device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
96 MHz	295	15.8 %	92.6 %	140
120 MHz	1551	82.8 %	43.4 %	13

Possible channel usage

Actual channel usage

Time based channel usage

.5 Lillehammer

In this section the tables containing detailed result for the amount for Grey and White space for each knowledge level in Lillehammer are presented.

KN1: all 5 MUX'es	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	99.00	1.00	0.00
Percentage of the total area	21.48	0.22	0.00

KN 2: MUX 1	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	160.00	23.00	0.00
Percentage of the total area	34.71	4.99	0.00

KN2: MUX 2, 3, 4 and 5	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	307.00	118.00	0.00
Percentage of the total area	66.59	25.60	0.00

Time-period 1, MUX 1	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	211.00	41.00	0.00
Percentage of the total area	45.77	8.89	0.00

Time-period 1, MUX 2, 3, 4 and 5	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	452.00	426.00	313.00
Percentage of the total area	98.05	92.41	67.90

Time-period 2, MUX 1	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	207.00	60.00	0.00
Percentage of the total area	44.90	13.02	0.00

Time-period 2, MUX 2, 3, 4 and 5	**N= 3**	**N= 7**	**N= 17**
Number of none protected locations	427.00	335.00	137.00
Percentage of the total area	92.62	72.67	29.72

Table .11: Knowledge level 1, Lillhammer:The amount of Grey space for a **4 watt Fixed device**

Frequency amount	Amount of location	distinctly found at % of locations	total percentage of location	household locations
80 MHz	99	21.5 %	21.5%	0

Table .12: Knowledge level 1, Lillhammer:The amount of Grey space for a **100mW portable device**

Frequency amount	Amount of location	Percentage of location	household locations
120 MHz	990	21.5 %	0

Table .13: Knowledge level 2, Lillhammer:The amount of Grey space for a **4 W fixed device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
64 MHz	147	31.9 %	78.54 %	54
80 MHz	160	34.7 %	53.85 %	1

Table .14: Knowledge level 2, Lillhammer:The amount of Grey space for a **100mW portable device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
96 MHz	147	31.9 %	66.6 %	54
120 MHz	160	34.7 %	34.7 %	1

Table .15: Knowledge level 3.1, Lillhammer:The amount of Grey space for a **4 W fixed device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
16 MHz	3	0.7 %	98.7 %	168
64 MHz	81	17.6 %	98 %	168
80 MHz	58	12.6 %	80.5 %	114
96 MHz	163	35.4 %	67.9 %	107
120 MHz	150	32.5 %	32.5 %	10

Table .16: Knowledge level 3.1, Lillhammer:The amount of Grey space for a **100mW portable device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
24 MHz	3	0.7 %	98.7 %	168
96 MHz	244	52.9 %	98.0 %	168
120 MHz	208	45.1 %	45.1 %	17

Table .17: Knowledge level 3.2, Lillhammer:The amount of Grey space for a **4 W fixed device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
16 MHz	7	1.5 %	94.1 %	156
64 MHz	160	34.7 %	92.6 %	154
80 MHz	130	28.2 %	57.9 %	47
96 MHz	67	14.5 %	29.7 %	38
120 MHz	70	15.2 %	15.2 %	3

Table .18: Knowledge level 3.2, Lillhammer :The amount of Grey space for a **100mW portable device**

Frequency amount	Amount of location	distinctly found at % of location	total percentage of location	household locations
24 MHz	7	1.5 %	94.1 %	156
96 MHz	227	49.2 %	92.6 %	154
120 MHz	200	43.4 %	43.4 %	12